The Nucleus as a QCD Laboratory

Exploring the new QCD frontier of color propagation, neutralization, and fluctuations

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Brookhaven National Laboratory

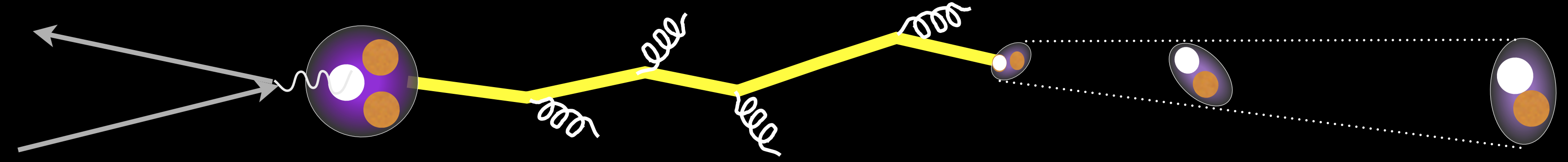
Overview

Hadronization studies are rich and fascinating

New technical capabilities open a new QCD frontier: nuclei+identified hadrons+kinematic reach to access color propagation, neutralization, and fluctuations

An excellent Year-1 program can be carried out with either EIC design, with the potential for dramatic scientific breakthroughs in our understanding of QCD. A second-generation program of studies can clearly follow, taking advantage of subsequent increases in luminosity and energy reach

Fascination with fragmentation



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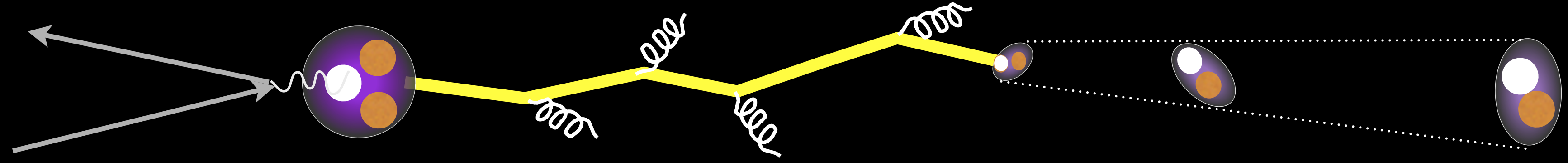

- Impossible

from a classical viewpoint

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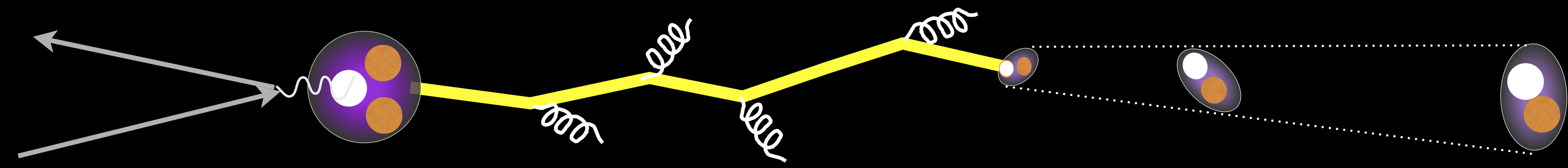

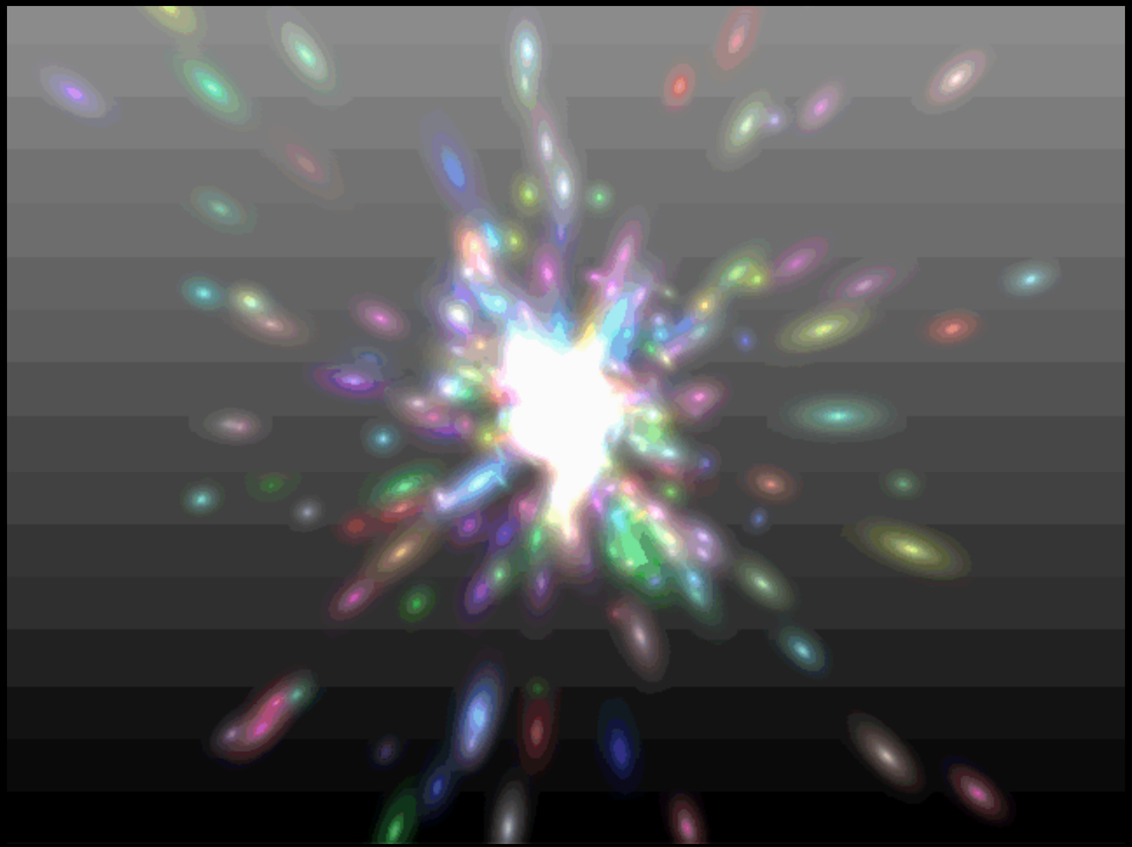

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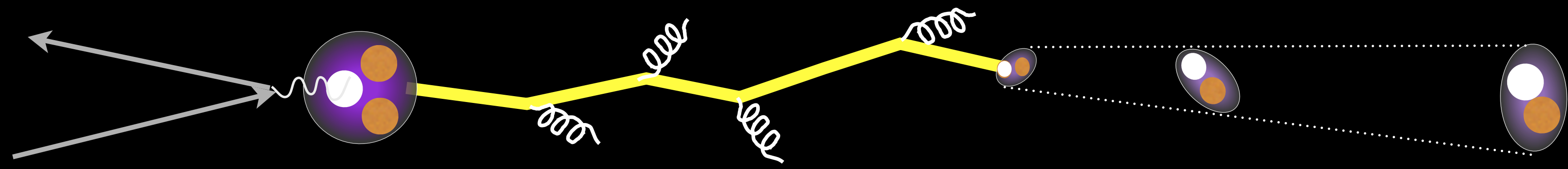
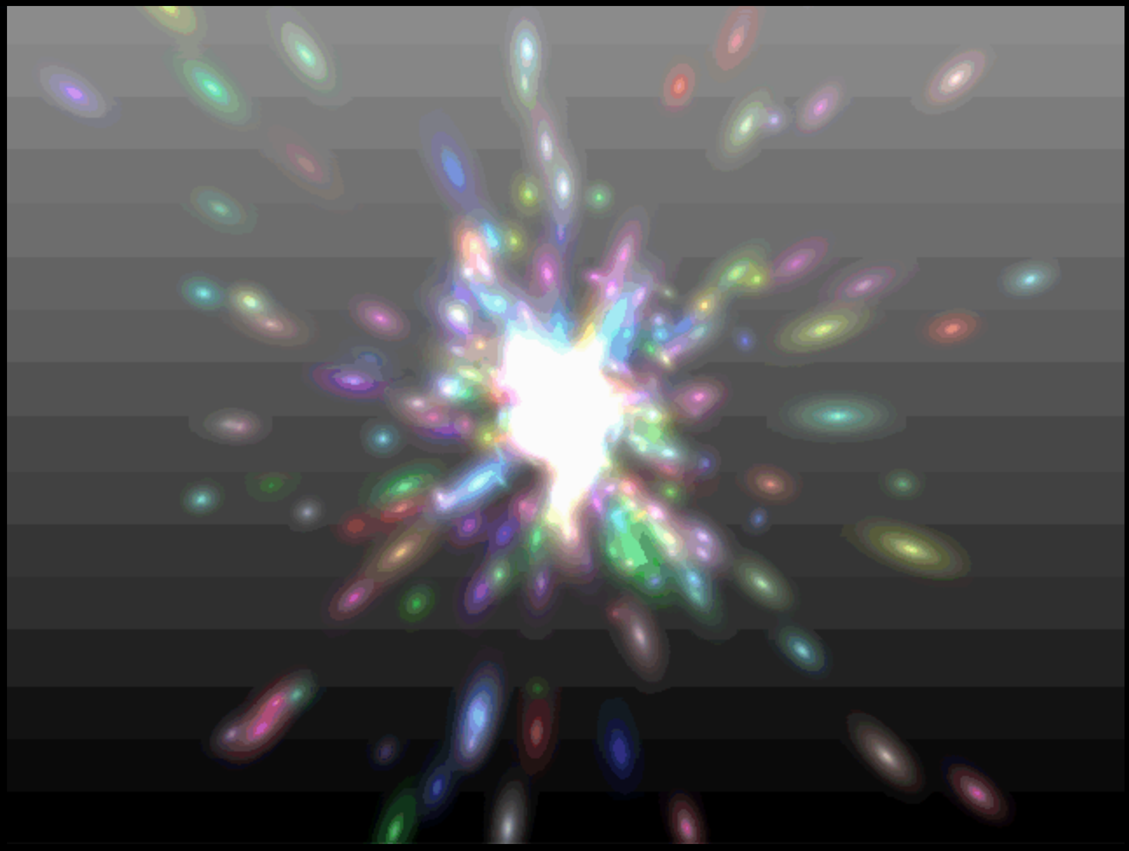


- **Impossible**

from a classical viewpoint

- **Unintuitive**

non-Abelian dynamics



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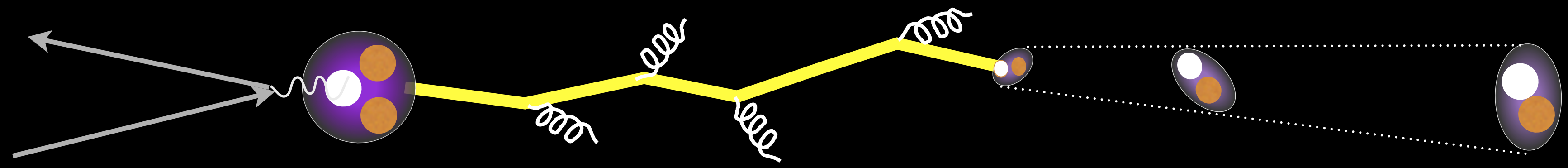

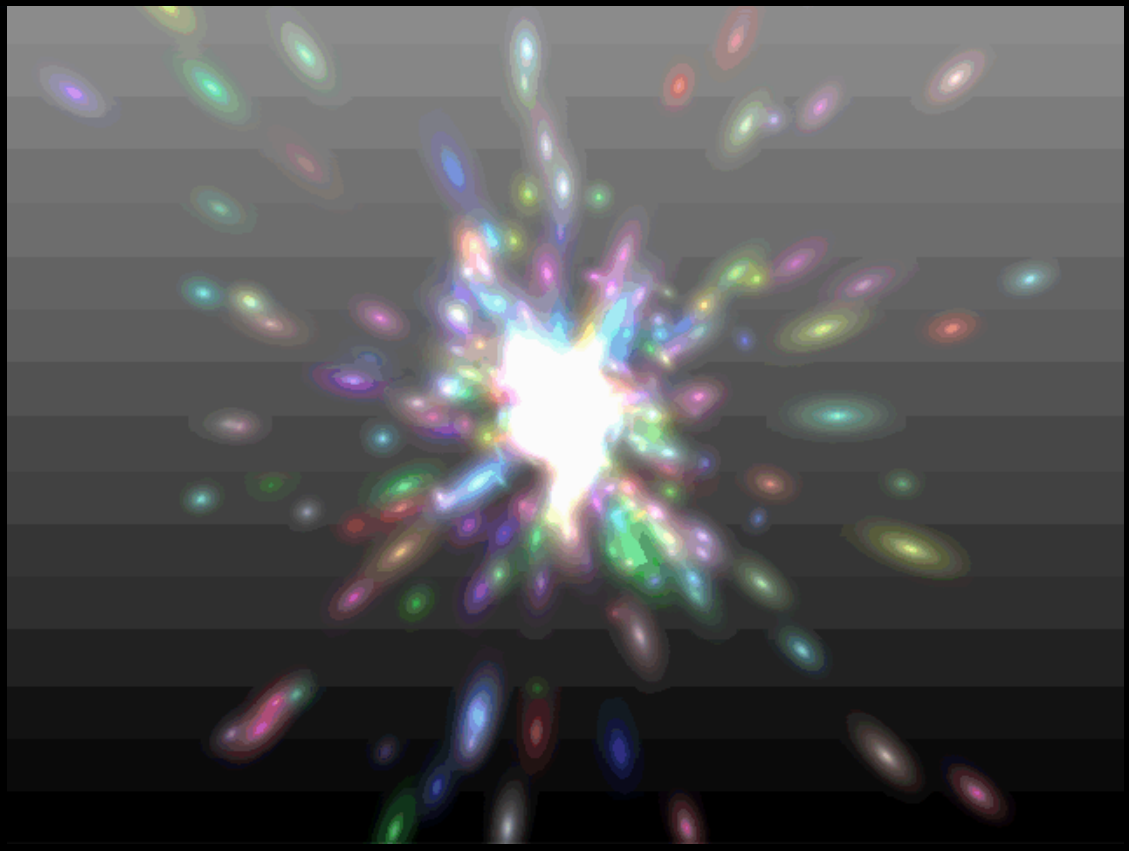

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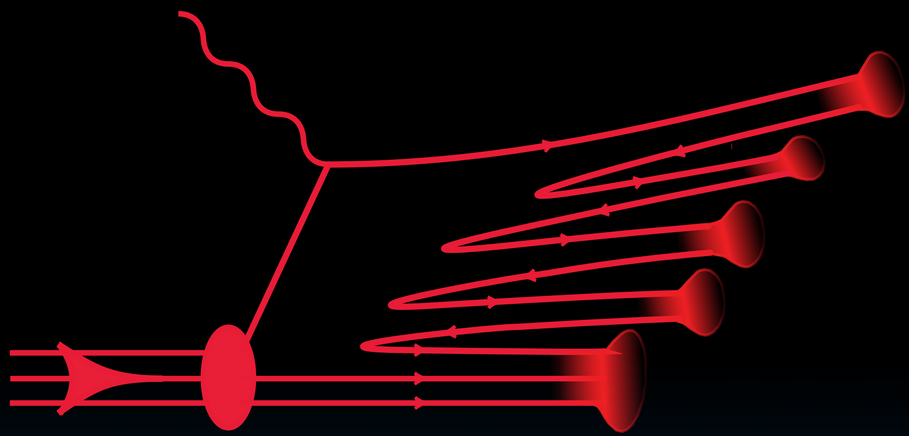

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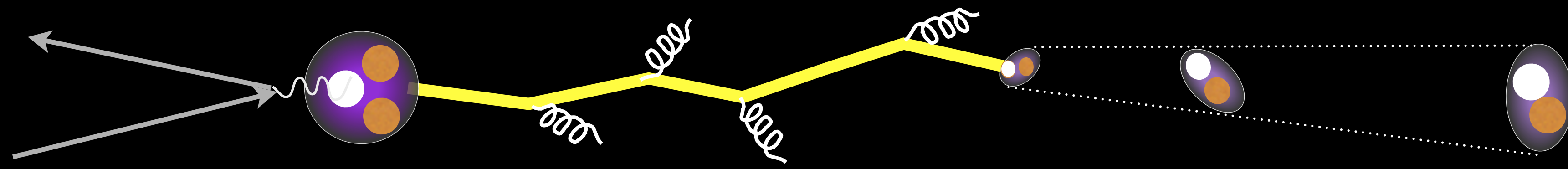

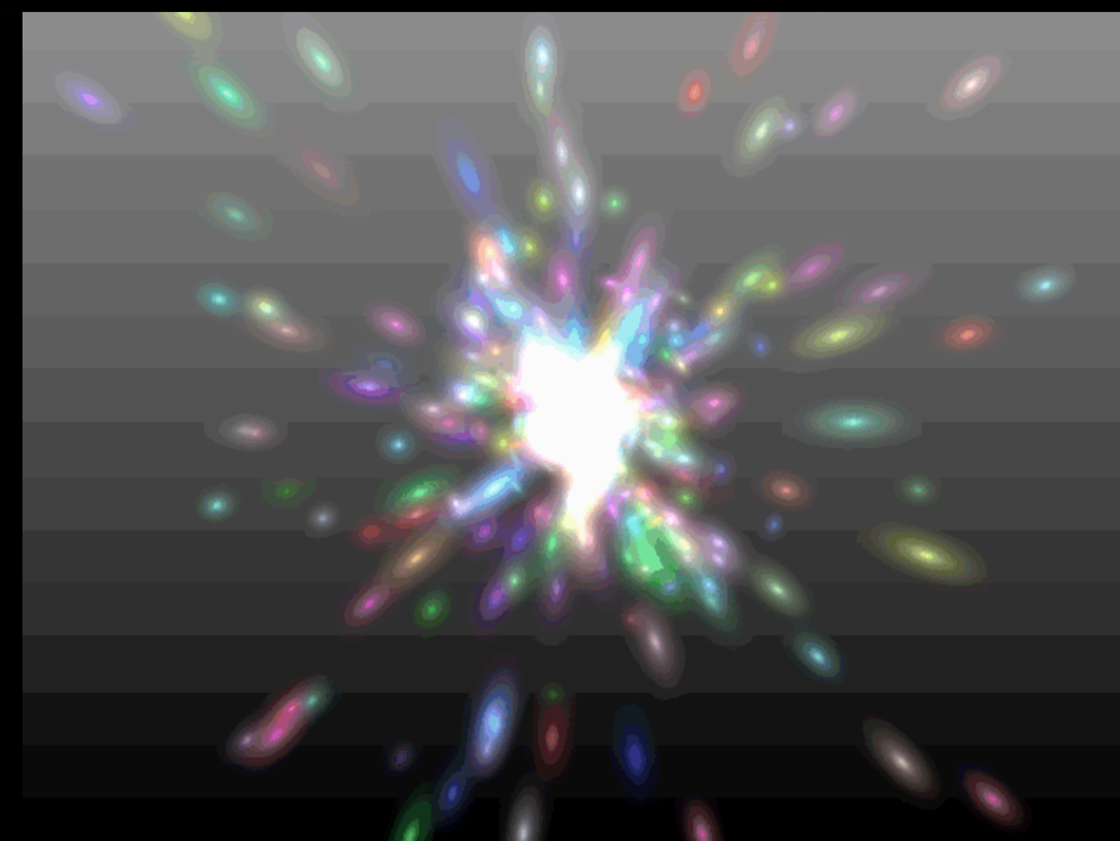

Impossible

from a classical viewpoint

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Ubiquitous

~all hard interactions

Physics thrusts

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Timescales

Virtual quark lifetime, hadron formation time

Measure: p_T broadening, flavor dependence of hadron attenuation

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Coherence

Partonic energy loss: QCD LPM effect, L^2 dependence of dE/dx

Measure: p_T broadening, hadron attenuation in heavy quark systems

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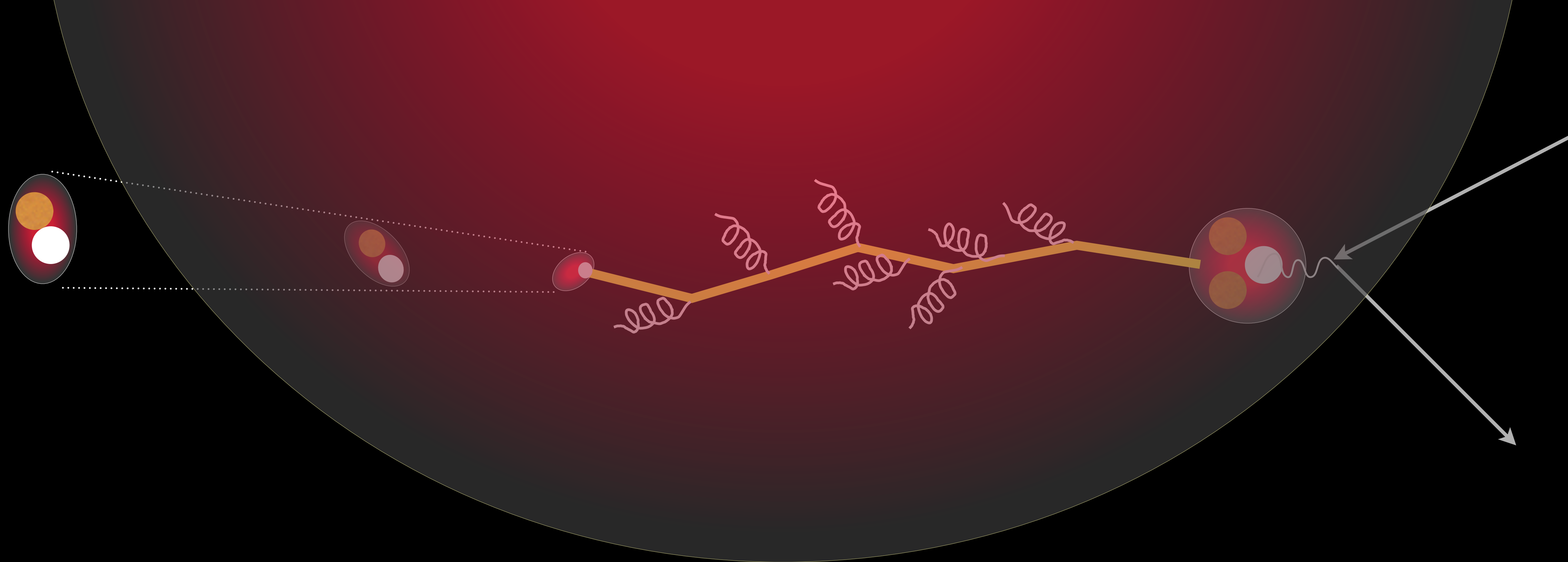
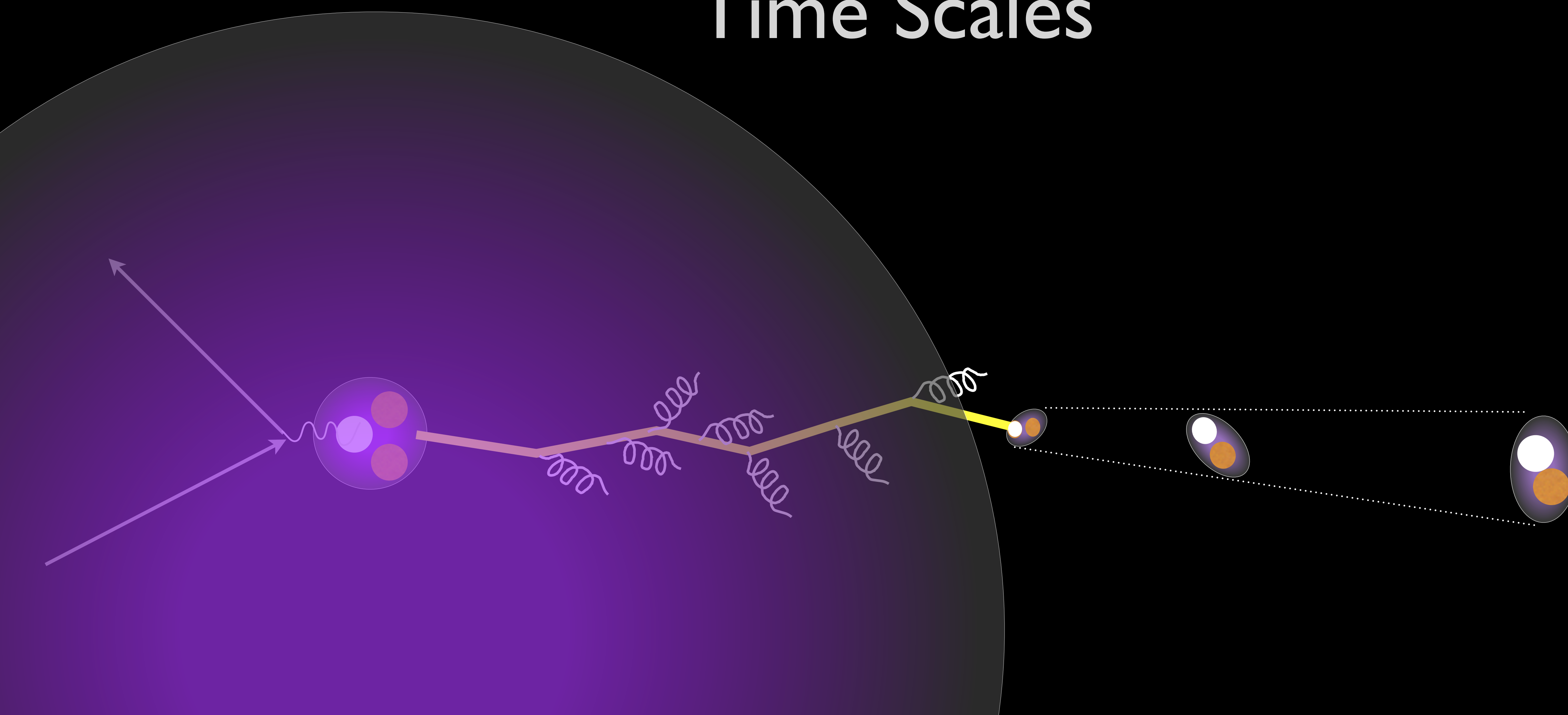
Mechanisms

Hadrons from quarks and gluons? Go beyond the string/cluster dichotomy for QCD cascade? How target baryon wavefunction recovers from losing struck quark? New fragmentation functions for proton and nuclear targets

Measure: two-hadron correlations, photon-hadron correlations, target fragmentation, hadron yields



Time Scales



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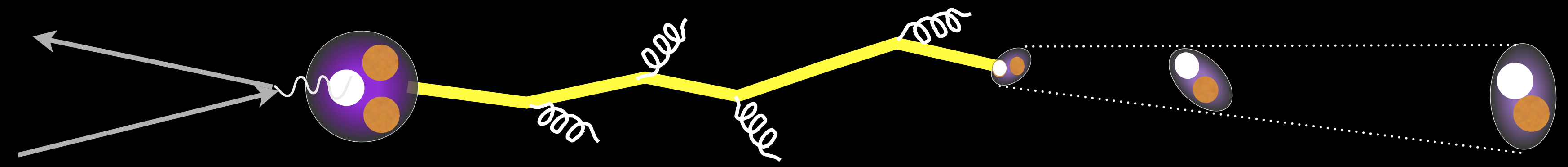


Two distinct stages for struck quark in DIS:

Virtual quark lifetime - gluons radiated

Hadron formation time

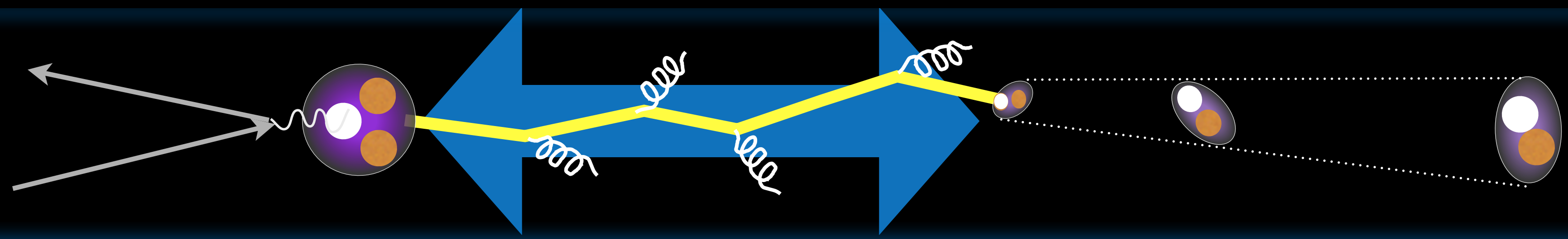
$\frac{k_{\|}}{k_{\perp}^{2}}$ *Overall time, just as in QED*

Theoretical speculation until now

Interactions with nuclei reveal time/distance scales

Bose-Einstein correlations too

Timescales



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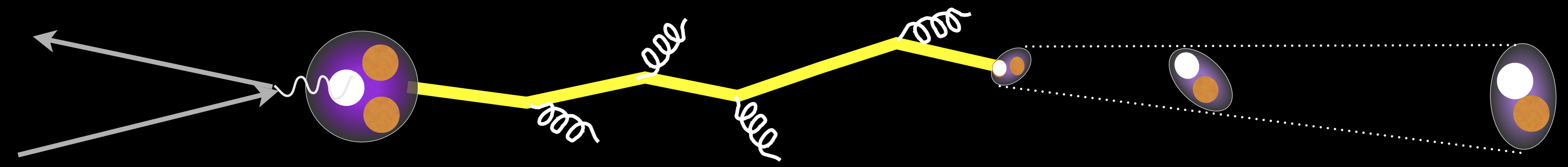

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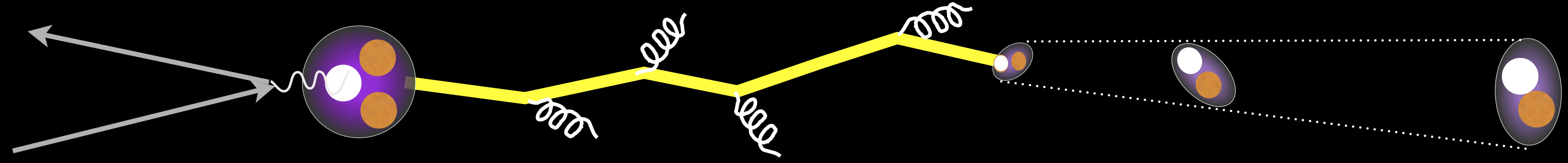

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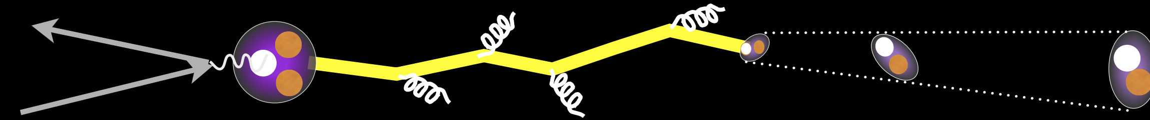
Time estimates - basic expectations



Light quarks:

$$\tau^{formation}_{q\to hadron} \approx \frac{E_q}{m_q} R_{hadron} \approx E_q R^2_{hadron}$$

$$\approx \nu R^2_{hadron} \qquad x > 0.1,\ \text{struck quark in hadron}$$

Bigger hadrons form much slower

Virtual photon energy ν=10 GeV, R(EM)=0.6 fm, τ=18 fm/c

Heavy quarks:

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Hadrons with heavy quarks form much faster

e.g., mass suppression for D0/pi is factor ~4

Reality: mass dependence + flavor dependence + mechanism dependences

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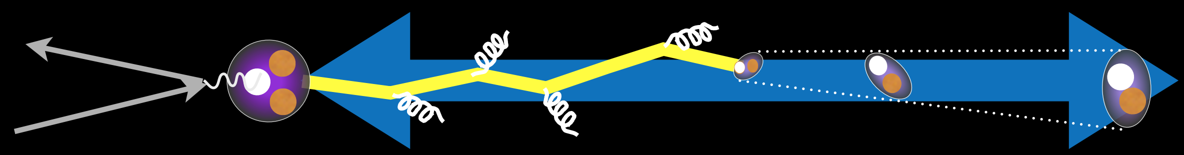

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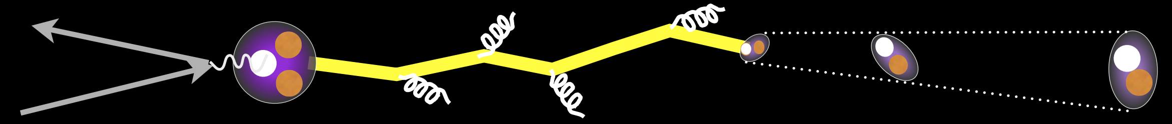

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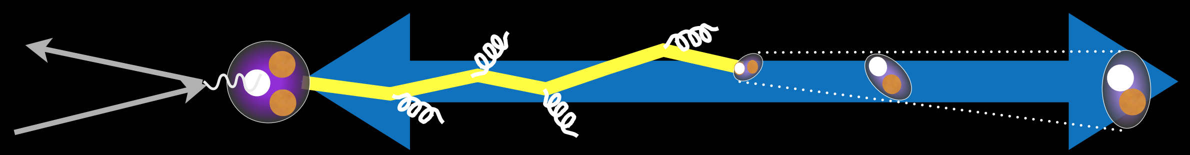
Timescales - how to measure?



- First observable: multiplicity ratio

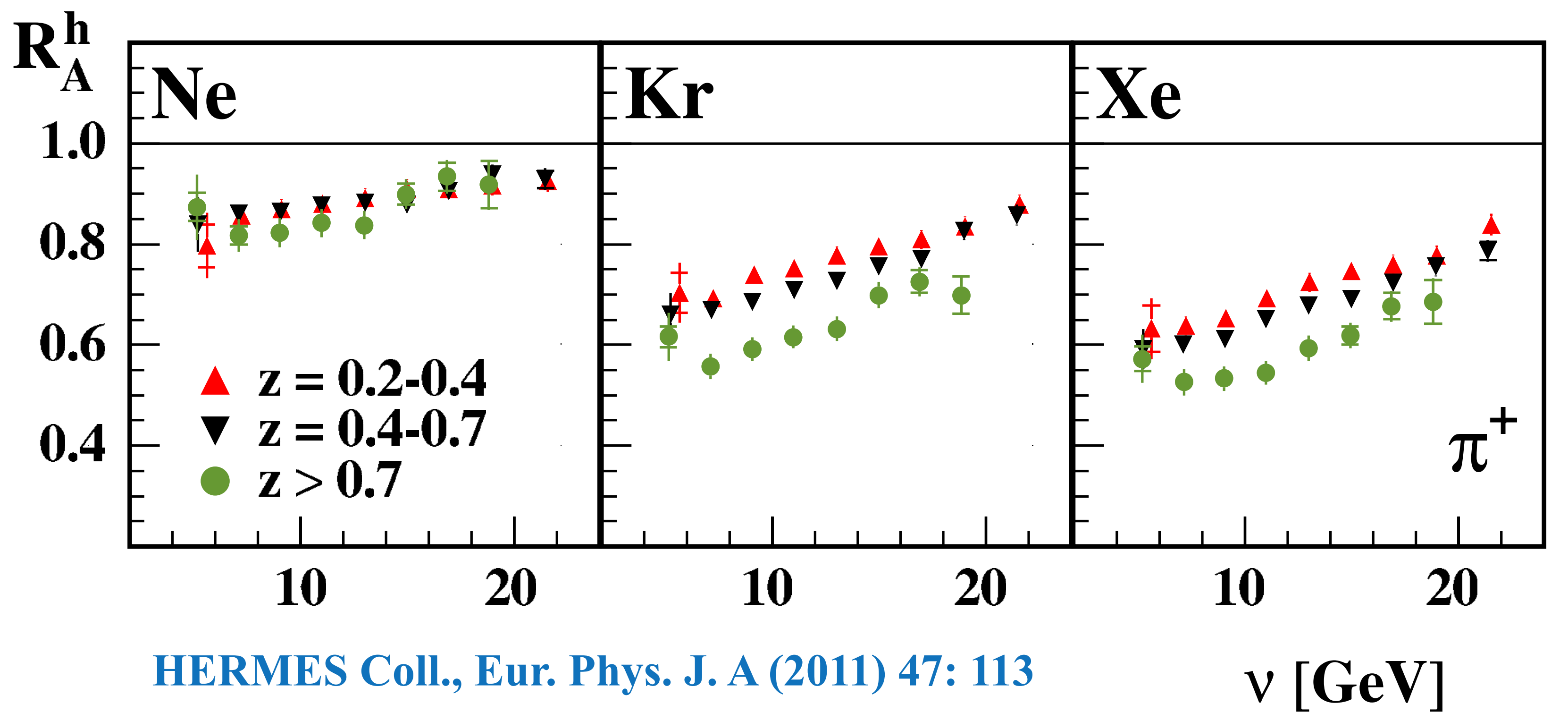
$$R_h = \frac{\frac{1}{N_e^A(Q^2,\nu)} N_h^A(Q^2,\nu,z,p_T)}{\frac{1}{N_e^D(Q^2,\nu)} N_h^D(Q^2,\nu,z,p_T)}$$

Expectations: rise→1 at high ν

- **Time dialation**, average pathlength in the medium

$$z \equiv \frac{E^{hadron}}{\nu}$$

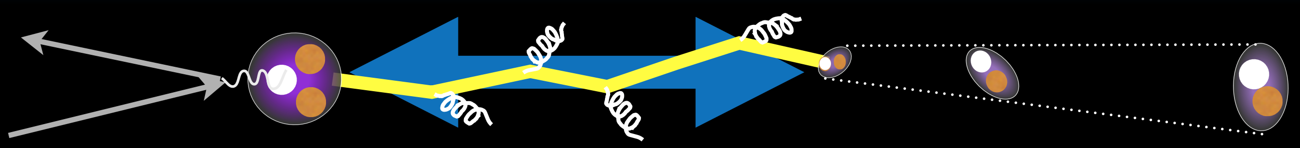
EIC Year 1



HERMES Coll., Eur. Phys. J. A (2011) 47: 113

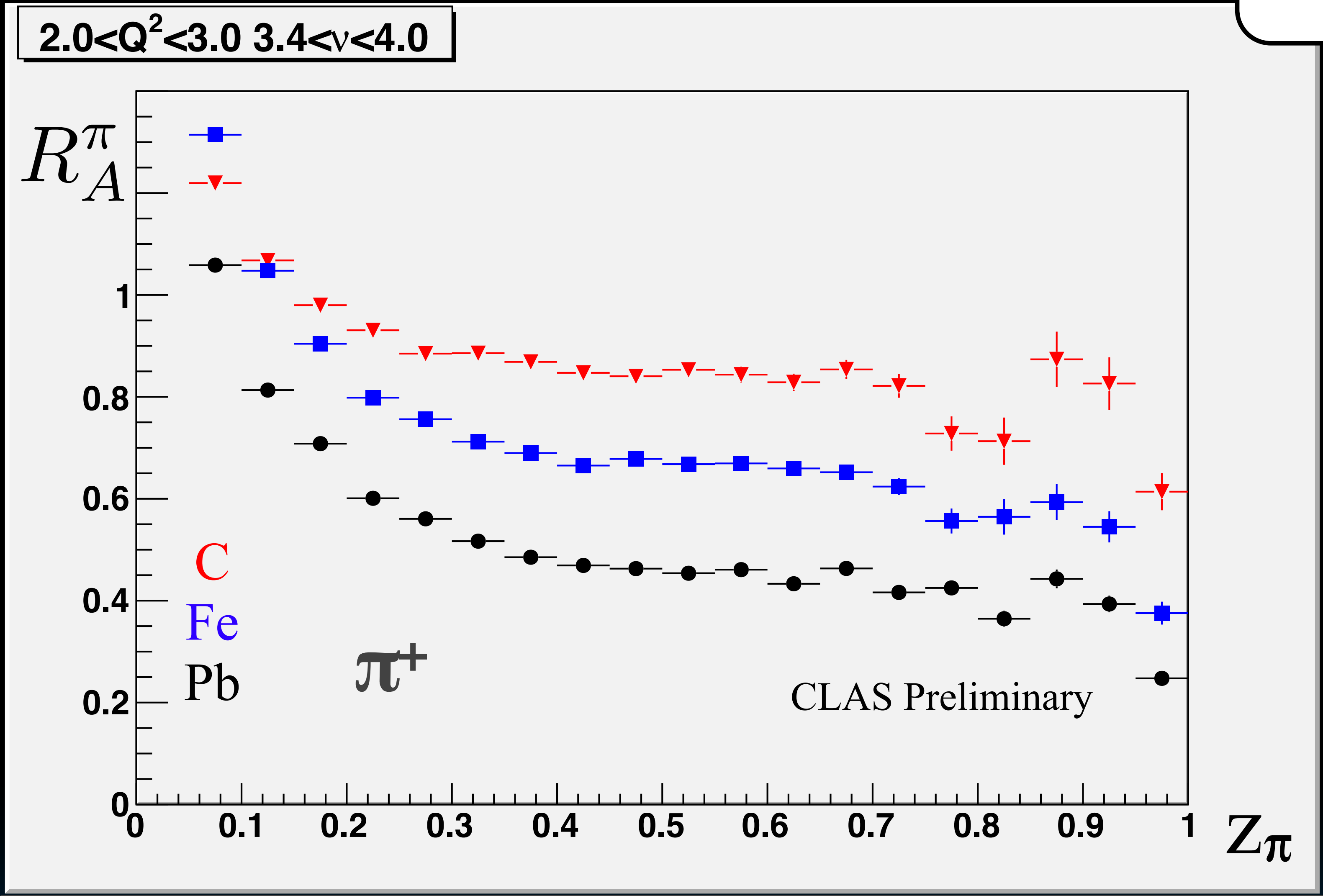
K.Gallmeister, U.Mosel, Nucl.Phys.A801:68-79,2008, arXiv:nucl-th/0701064 , time-based interpretation

Lund string model time estimate



- Virtual quark lifetime component, light quarks
- **z dependence**

$$l_p = z\frac{(ln(\frac{1}{z^2}) - 1 + z^2)}{1 - z^2}$$



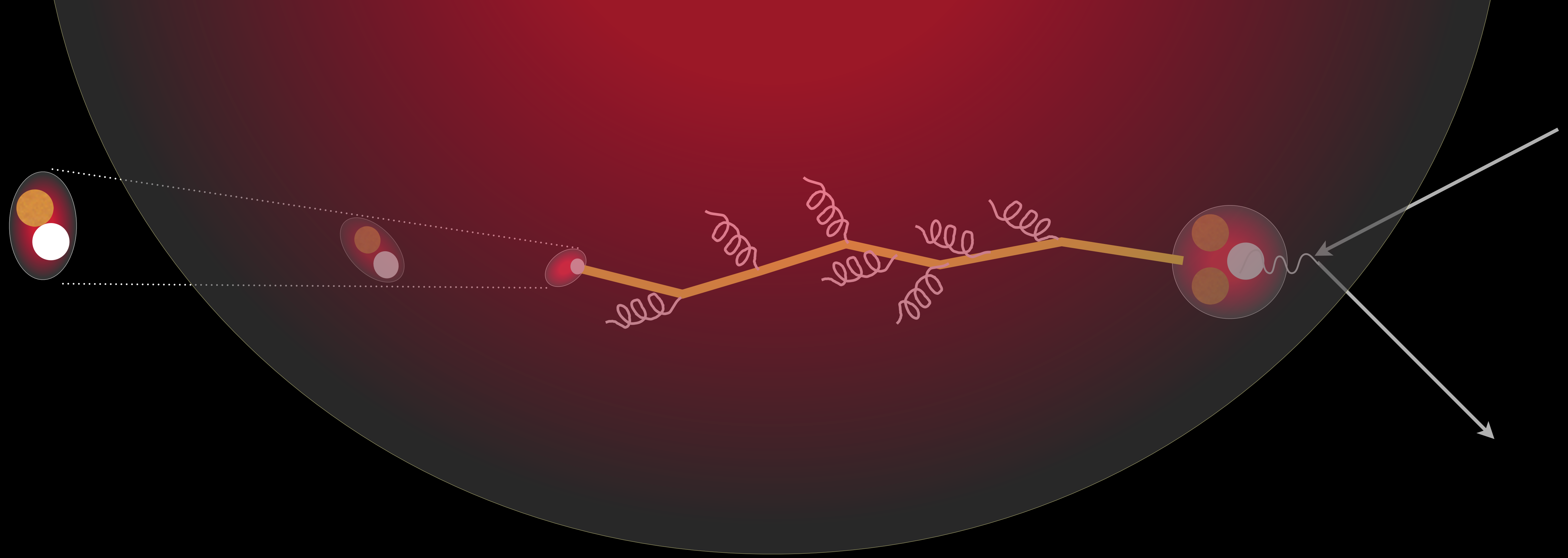
Expectation: drop at high z

Expectation: drop at low z, but obscured by other effects for R_A

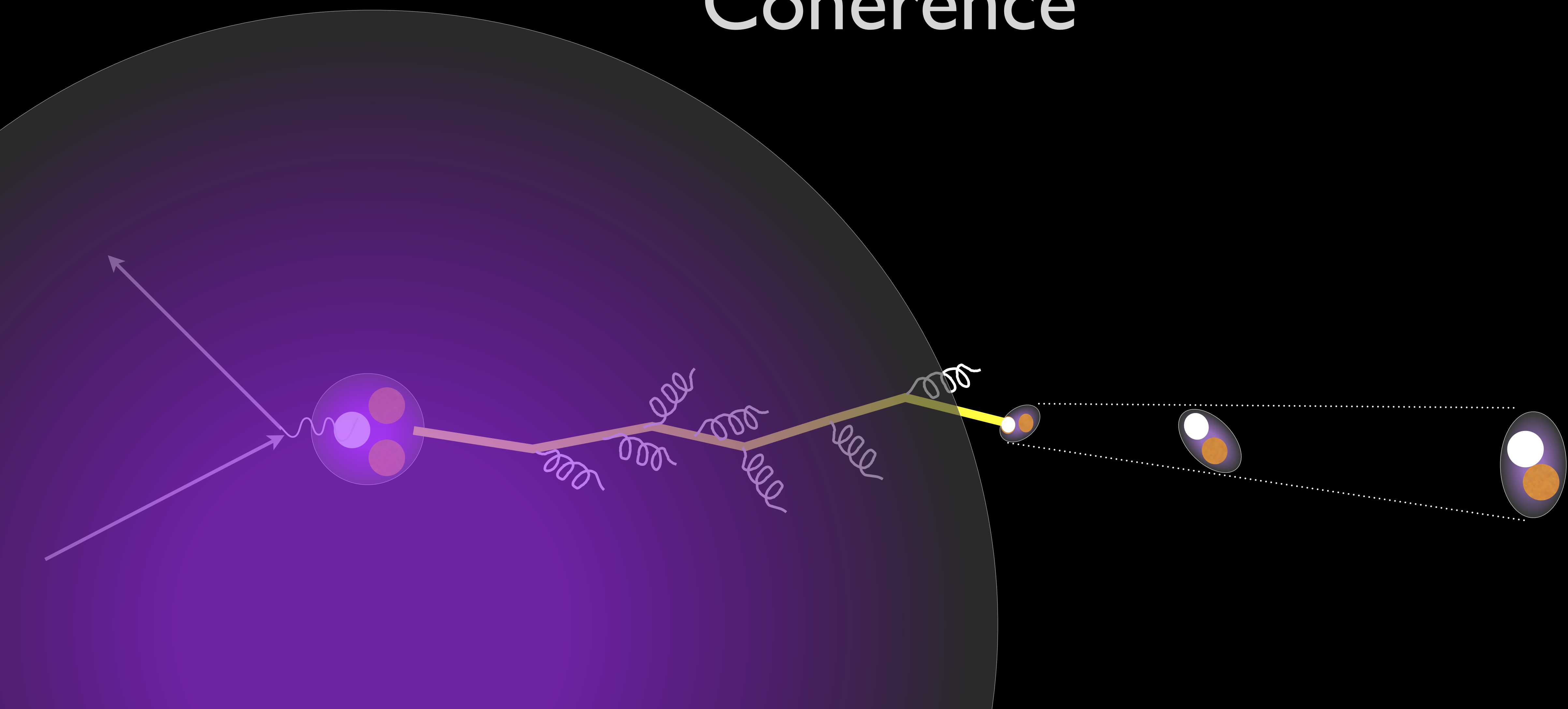
Maximum lifetime is at intermediate z

EIC Year 1

Test of string model time dependence



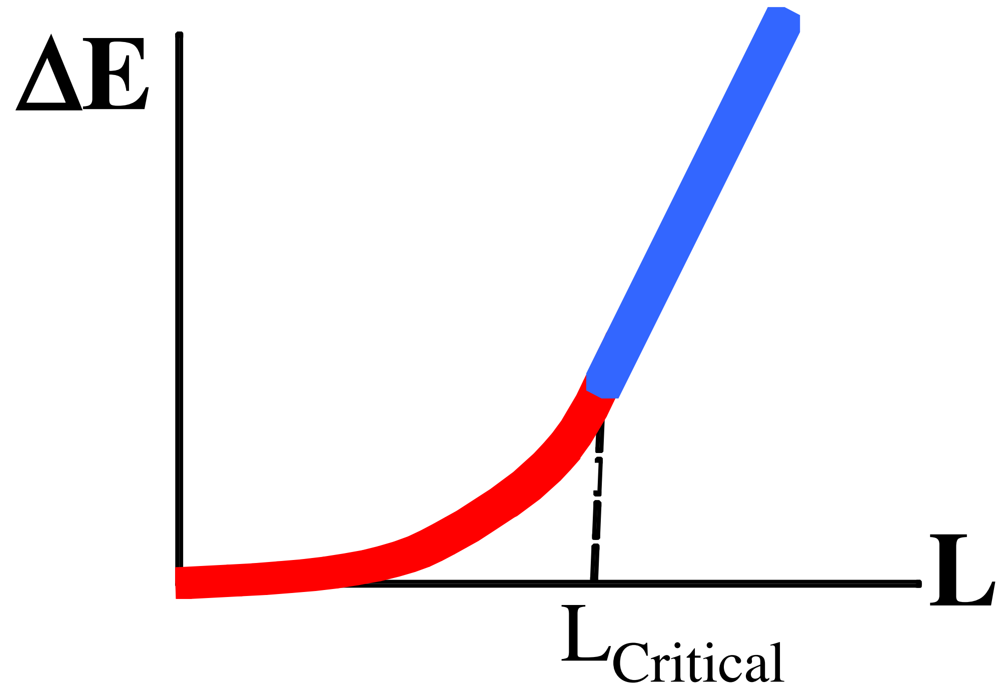
Coherence



Partonic energy loss in pQCD

$L < L_{Critical}$ $$-\frac{dE}{dx} \propto L\hat{q}$$

$L > L_{Critical}$ $$-\frac{dE}{dx} \propto \sqrt{E\hat{q}}$$



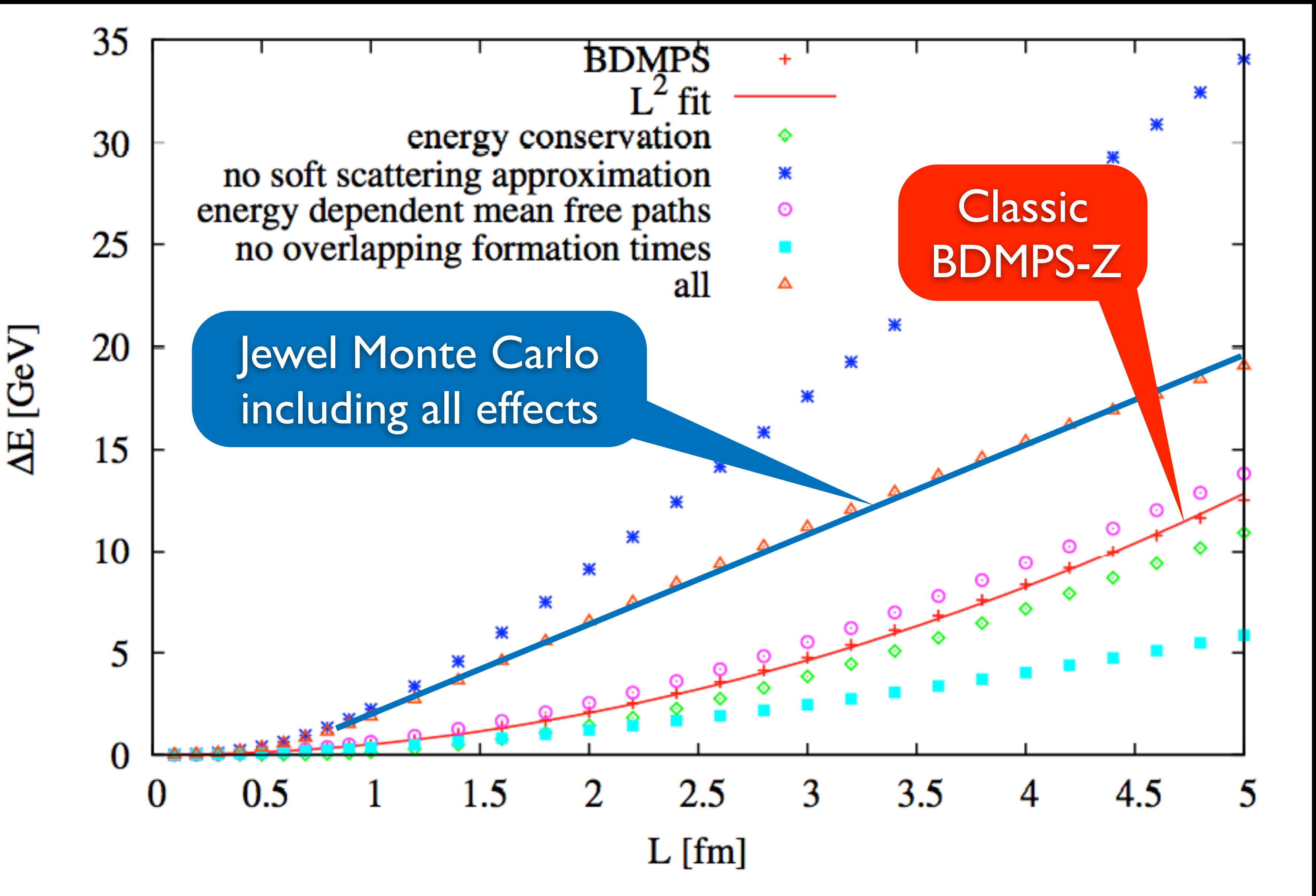
$$\text{at} \quad \mathrm{L} = \mathrm{L_{Critical}}, \quad \mathrm{L\hat{q}} \propto \sqrt{\mathrm{E_q} \cdot \hat{\mathrm{q}}} \;\; ; \quad \mathrm{L_{Critical}} \propto \sqrt{\frac{\mathrm{E_q}}{\hat{\mathrm{q}}}}$$

$$\mathrm{E_q} \approx \nu \approx \text{ few GeV}, \; \hat{\mathrm{q}} \approx 0.02 - 0.1 \text{ GeV}^2/\text{fm},$$

$$\longrightarrow \quad \sqrt{\frac{\mathrm{E_q}}{\hat{\mathrm{q}}}} \approx \mathrm{R_{lead}} - \mathrm{R_{carbon}}$$

Connection to p_T broadening observable: $$-\frac{dE}{dx} = \frac{\alpha_s N_c}{4} \Delta k_T^2$$

Energy loss in *hot dense matter*



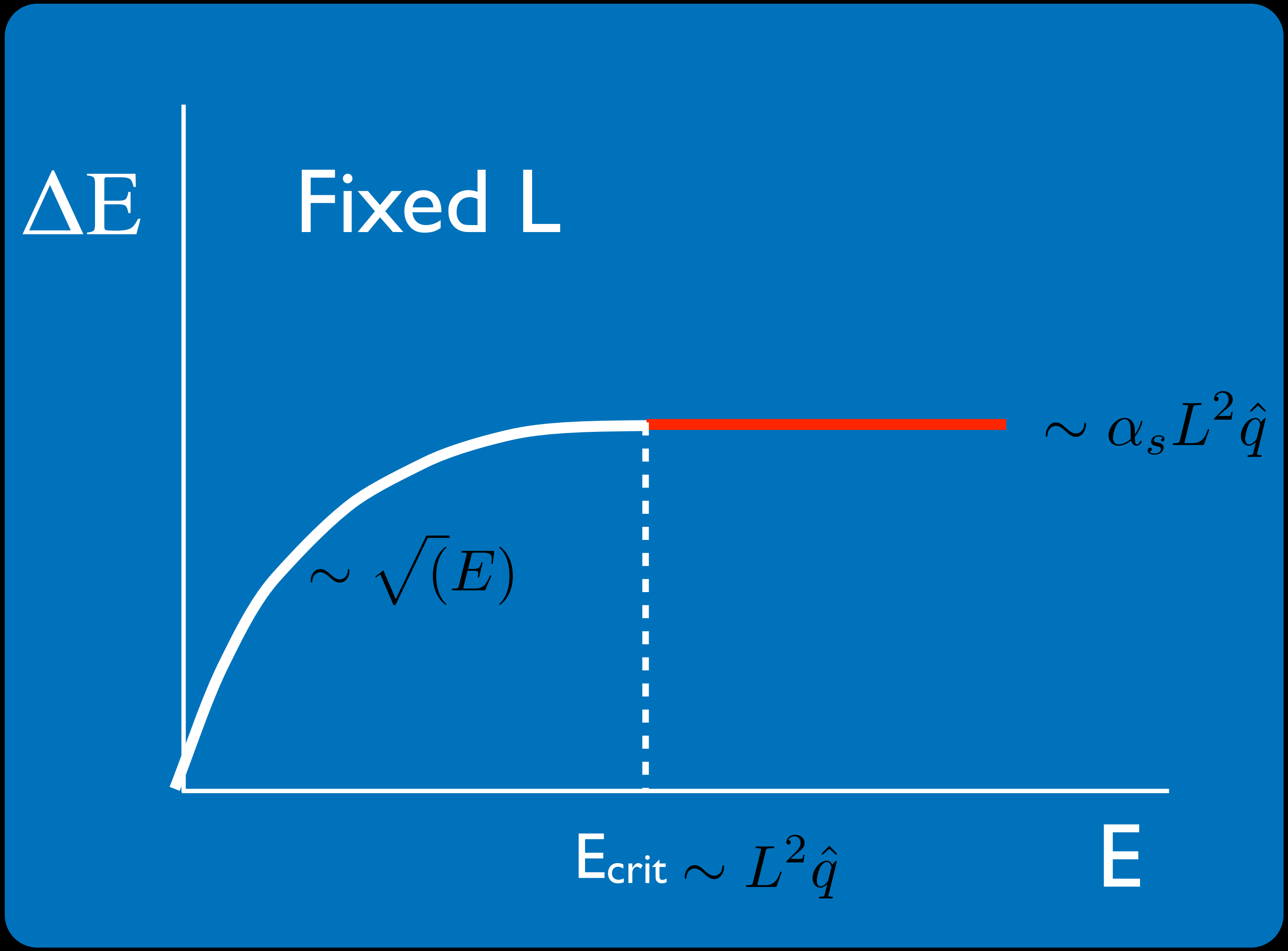
arXiv:1202.1192v1 [hep-ph]

arXiv:1311.0048v1 [hep-ph]

Zapp and Wiedemann find L^2 behavior washed out in realistic Monte Carlo calculation for hot dense matter

also, find more energy loss

Partonic energy loss in pQCD: E_{crit}



BDMPS-Z:

For *fixed* medium length *L* there is a critical energy E_{crit}

$L > L_{crit}$ is equivalent to $E < E_{crit}$

$$E_{crit} \approx 0.4 \cdot (\frac{L}{1\ fm})^2 \quad GeV$$

$$\Delta E \approx \alpha_s L \sqrt{E \hat{q}} \qquad (E << E_{cr})$$

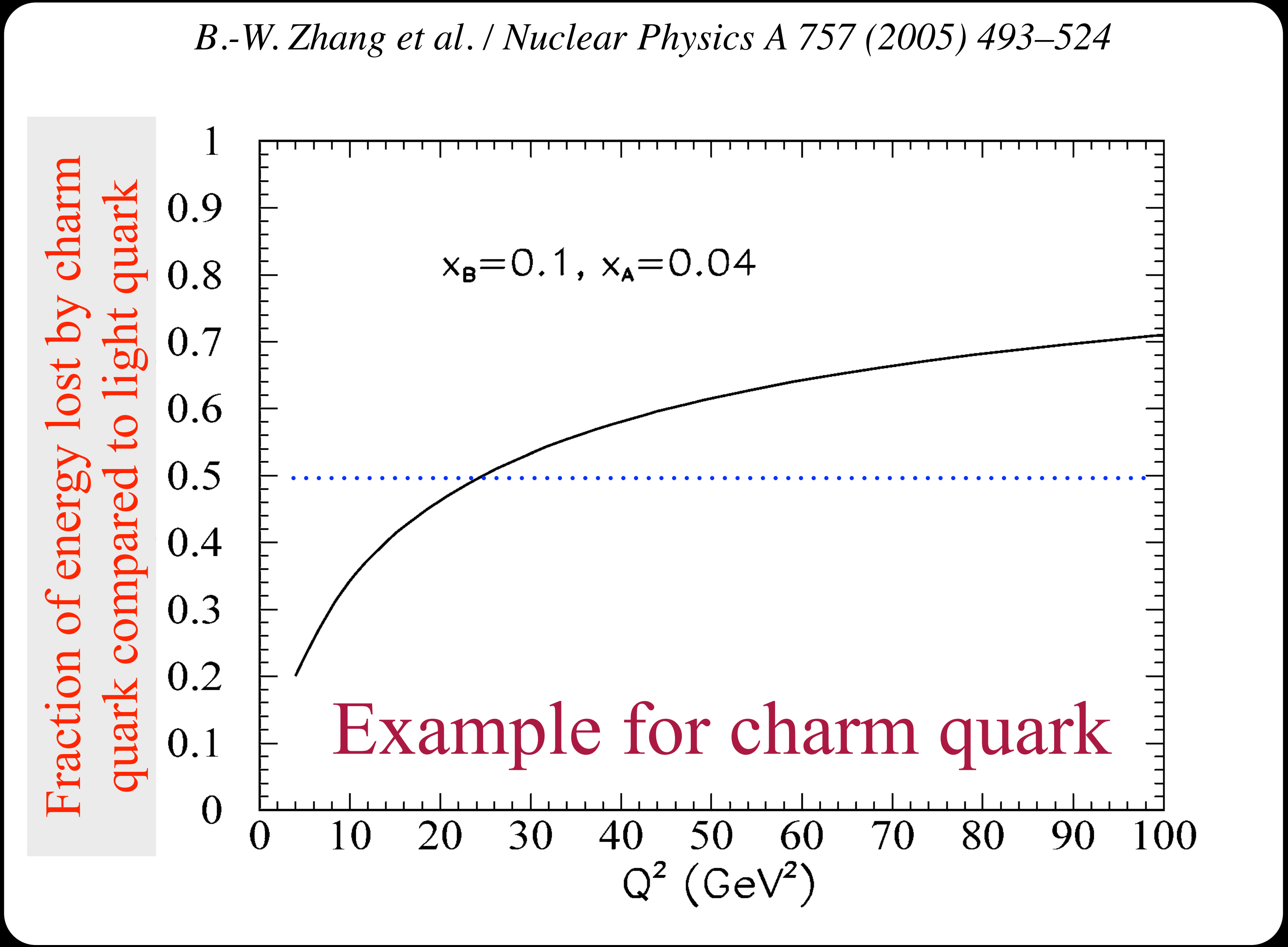
$$\Delta E \approx \alpha_s L^2 \hat{q} \qquad (E >> E_{cr})$$

Carbon: $E_{crit} = \nu = 2.5$ GeV
Lead: $E_{crit} = \nu = 17$ GeV
CLAS data in transition region!
CLAS12 will study this, but need EIC to get to sufficient ν

Heavy quark energy loss

Heavy quark radiative energy loss is predicted to be *less* than light quark energy loss

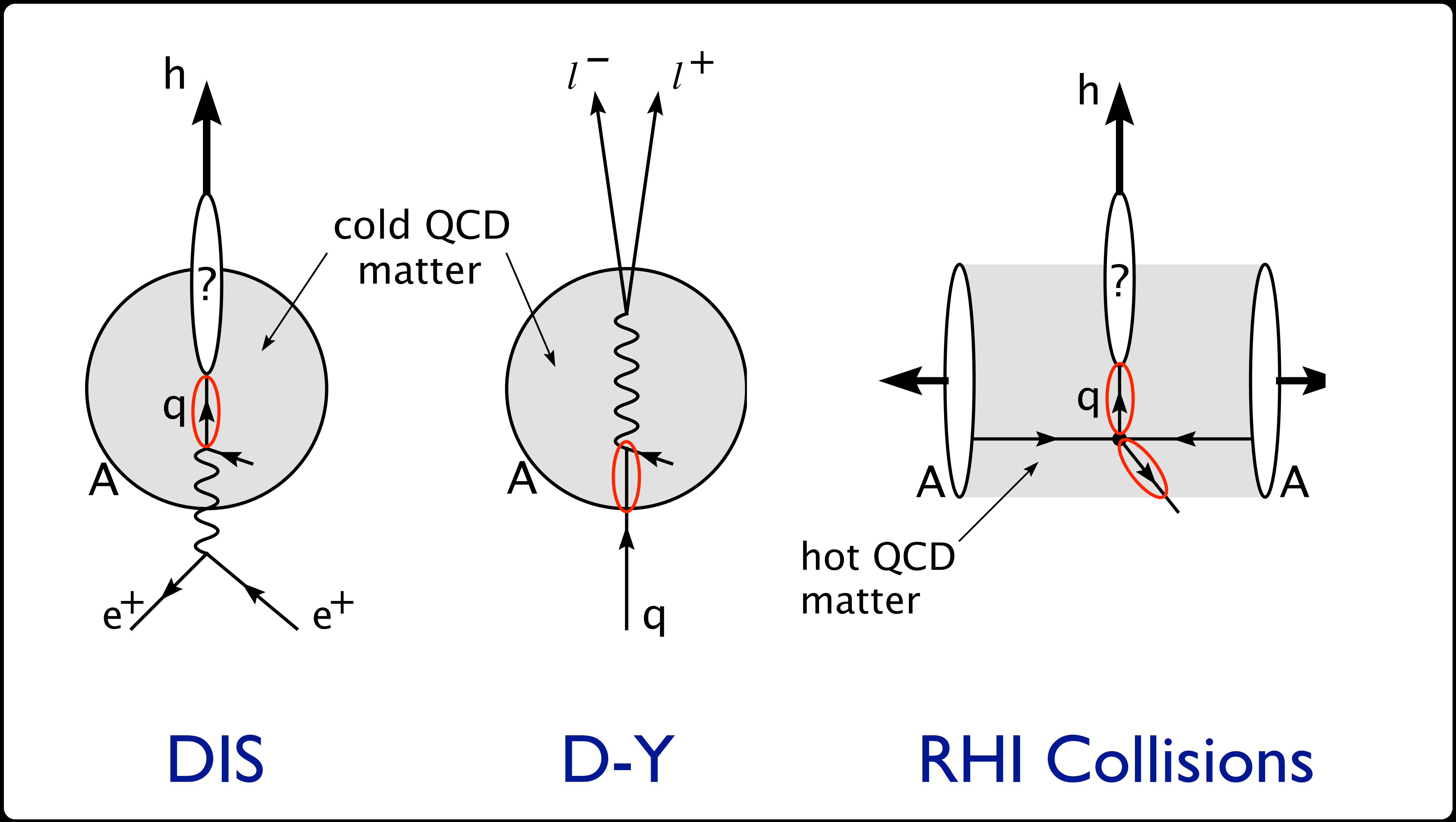
Formalism implies a strict ordering of quark energy loss: u/d, s, c, b



$$\frac{Q_H(k_T)}{Q_L(k_T)} \approx \exp[\frac{16\alpha_s C_F}{9\sqrt{3}} \cdot L \cdot (\frac{\hat{q}M^2}{M^2 + k_T^2})^{1/3}]$$

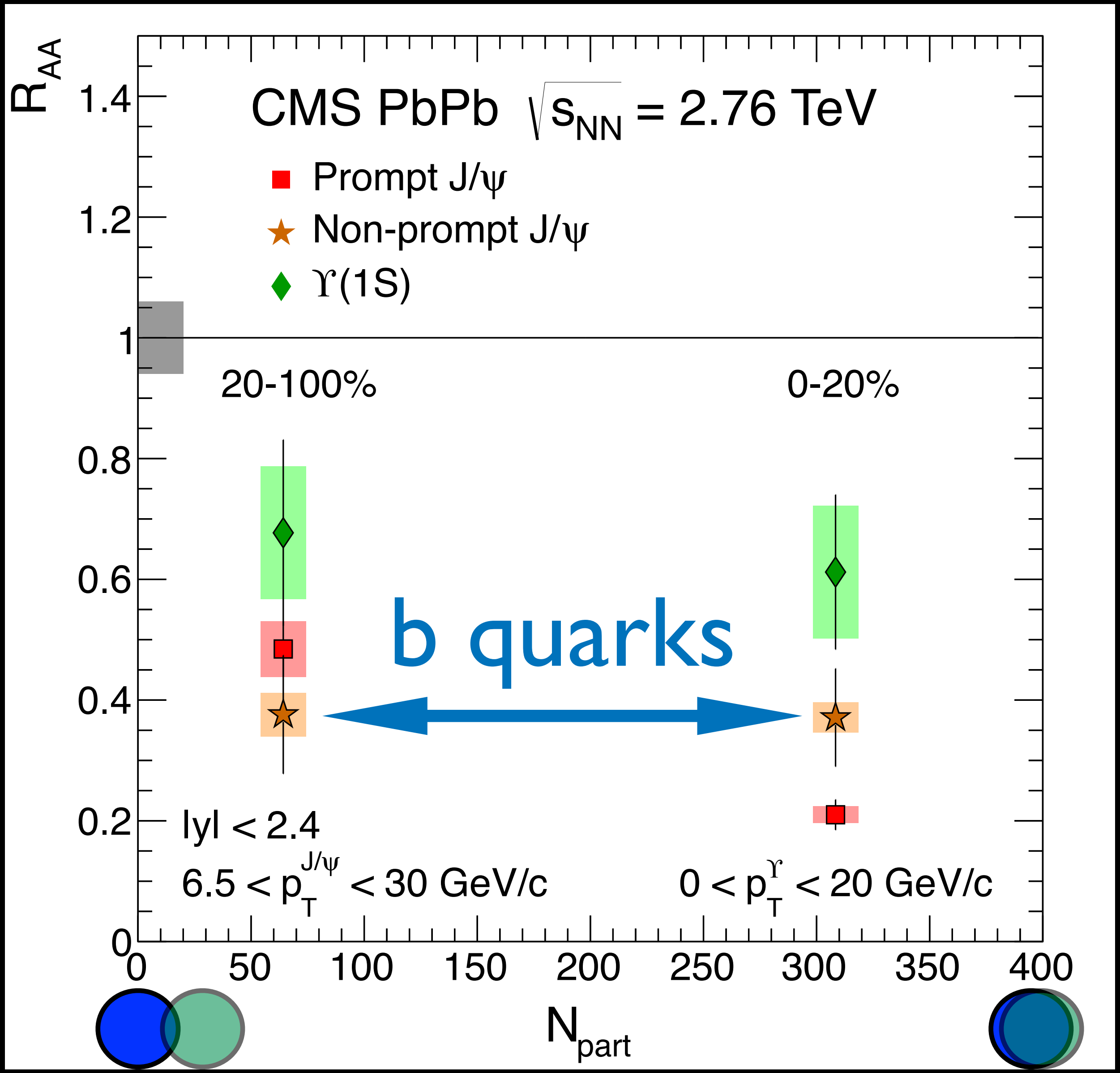
http://arxiv.org/abs/0810.5702, http://arxiv.org/abs/0907.1918

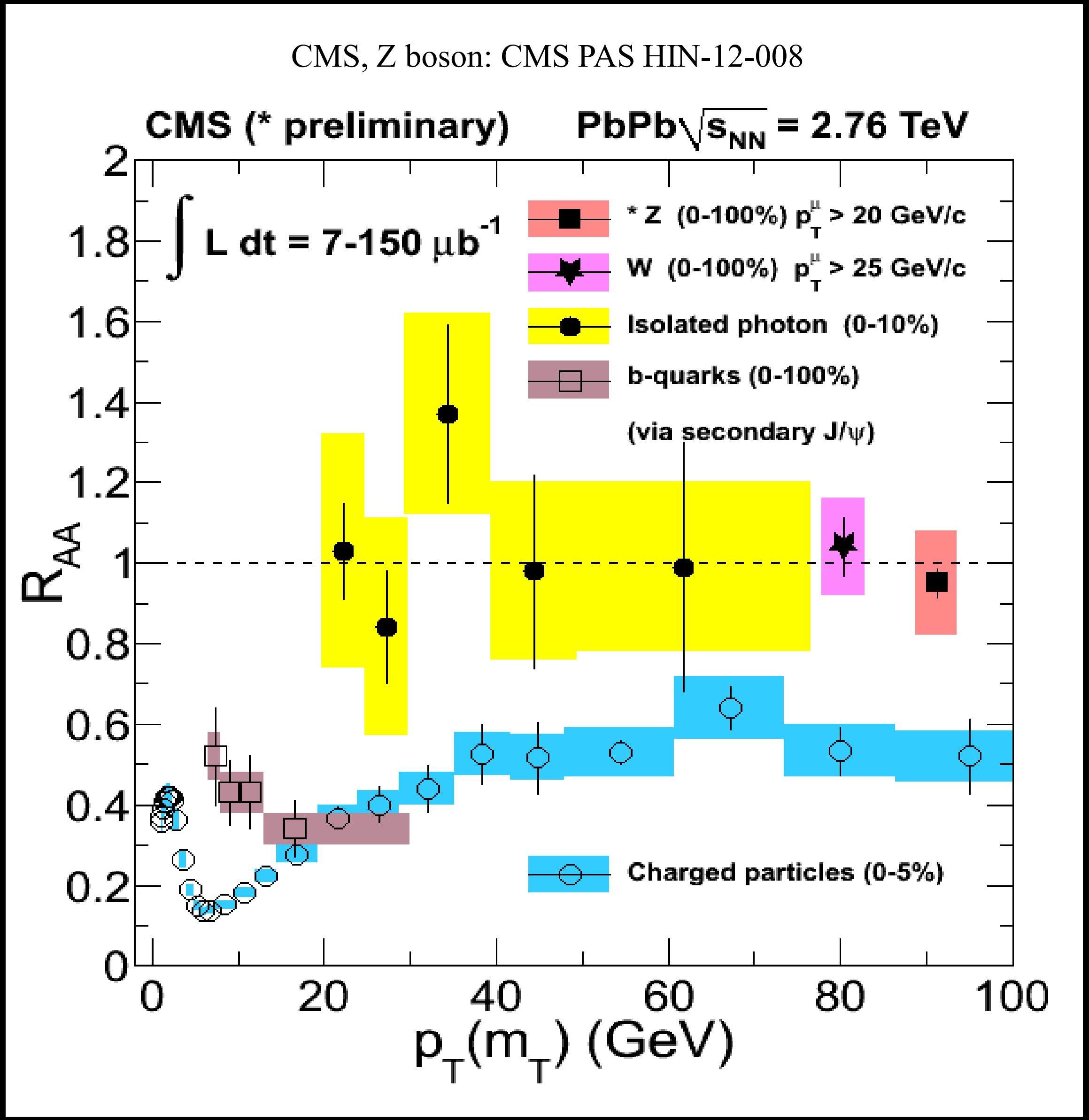
Parton Propagation in Three Processes



Accardi, Arleo, Brooks, d'Enterria, Muccifora Riv.Nuovo Cim.032:439-553,2010 [arXiv:0907.3534]
Majumder, van Leuween, Prog. Part. Nucl. Phys. A66:41, 2011, arXiv:1002.2206 [hep- ph]
S. Peigne, A.V. Smilga, Phys.Usp.52:659-685, 2009, arXiv:0810.5702v2 [hep-ph]

R_{AA} from CMS for PbPb collisions - Puzzles

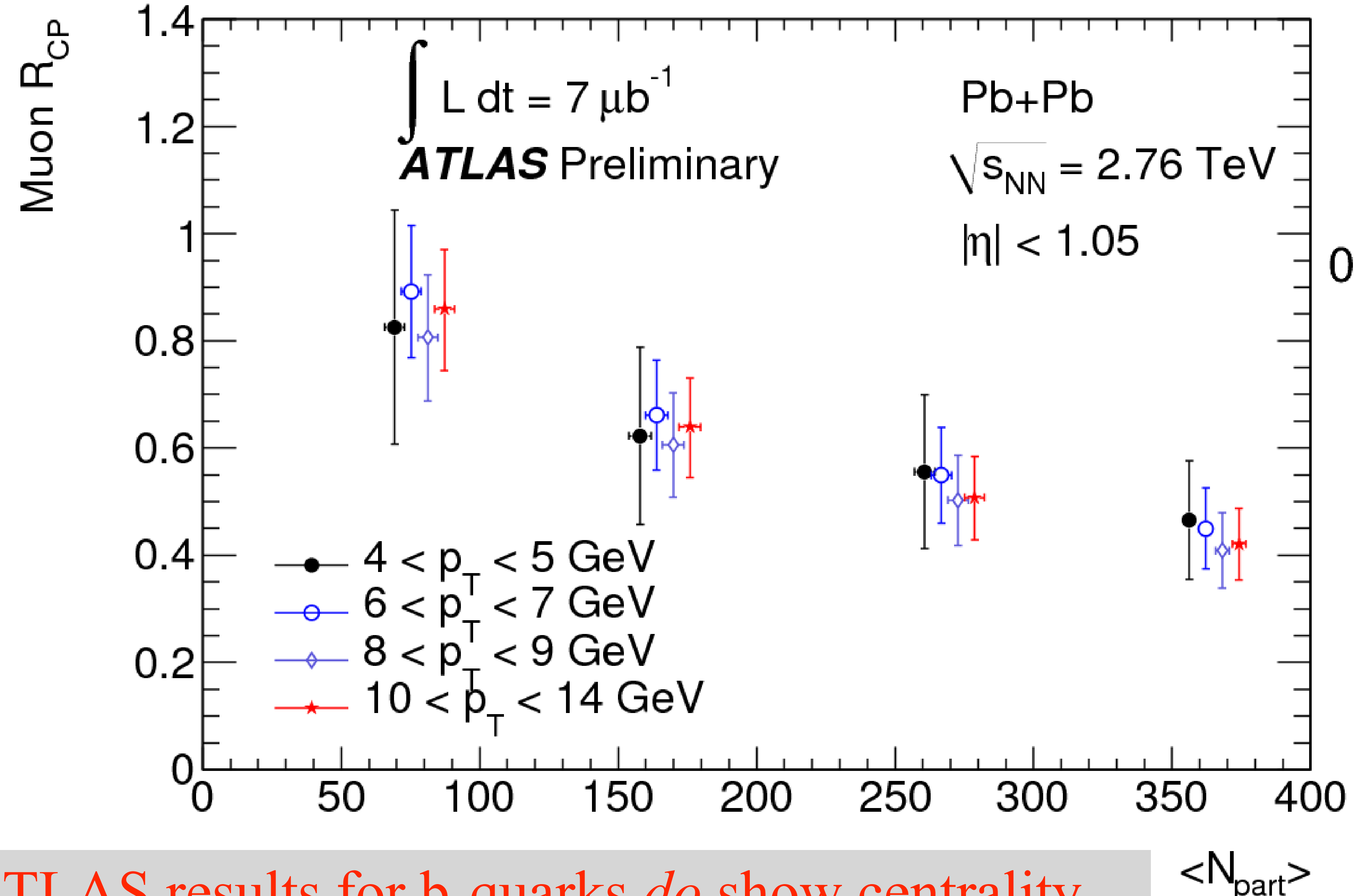


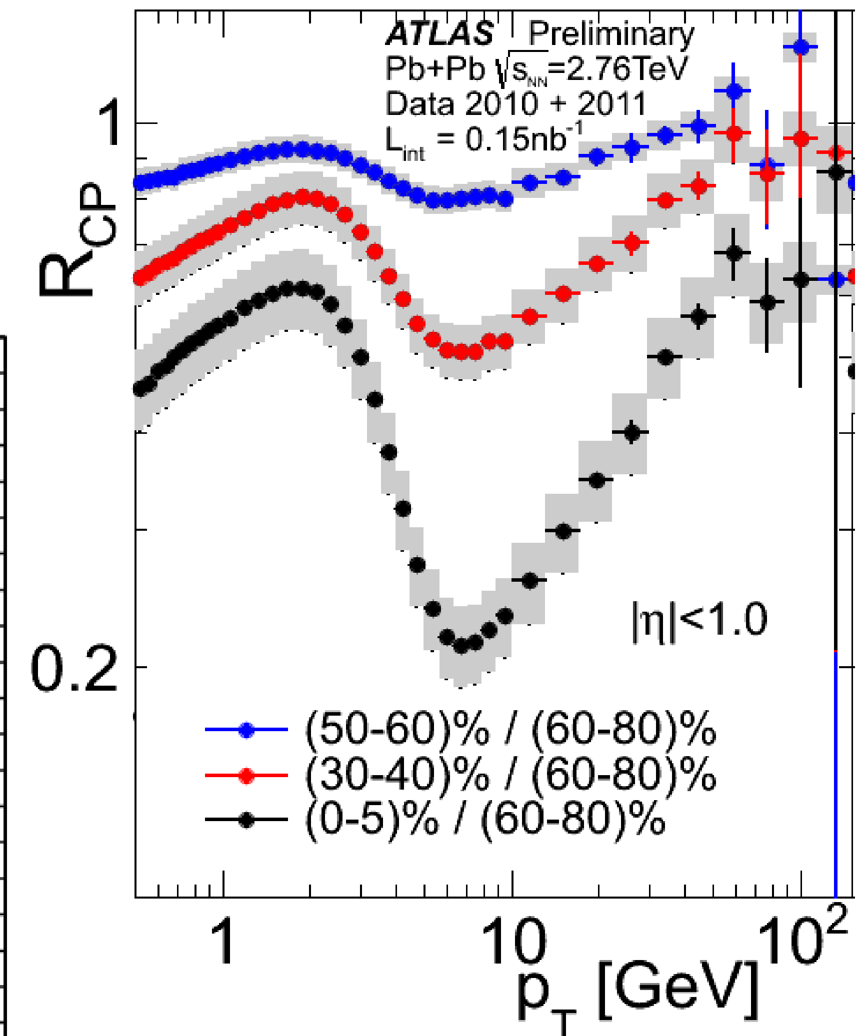


- Assuming non-prompt J/ψ represents b-quarks sampling the medium, a lack of centrality dependence is very surprising.
- Suppression is comparable to that of light quarks, but should be much less suppressed

ATLAS muon-tagged open heavy flavor

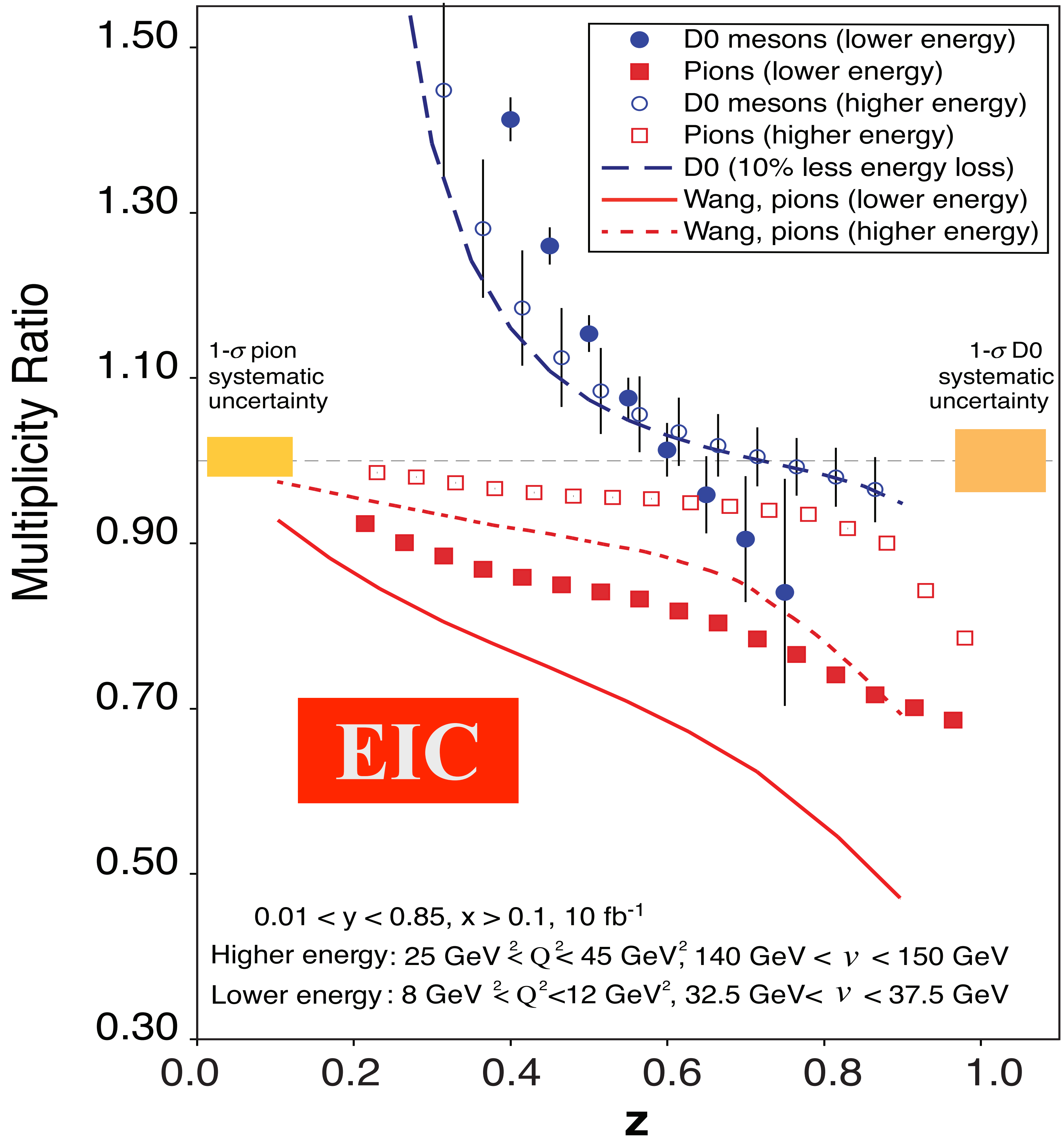
Results: $R_{\mathrm{CP}}(N_{\mathrm{part}})$ from heavy flavor decays



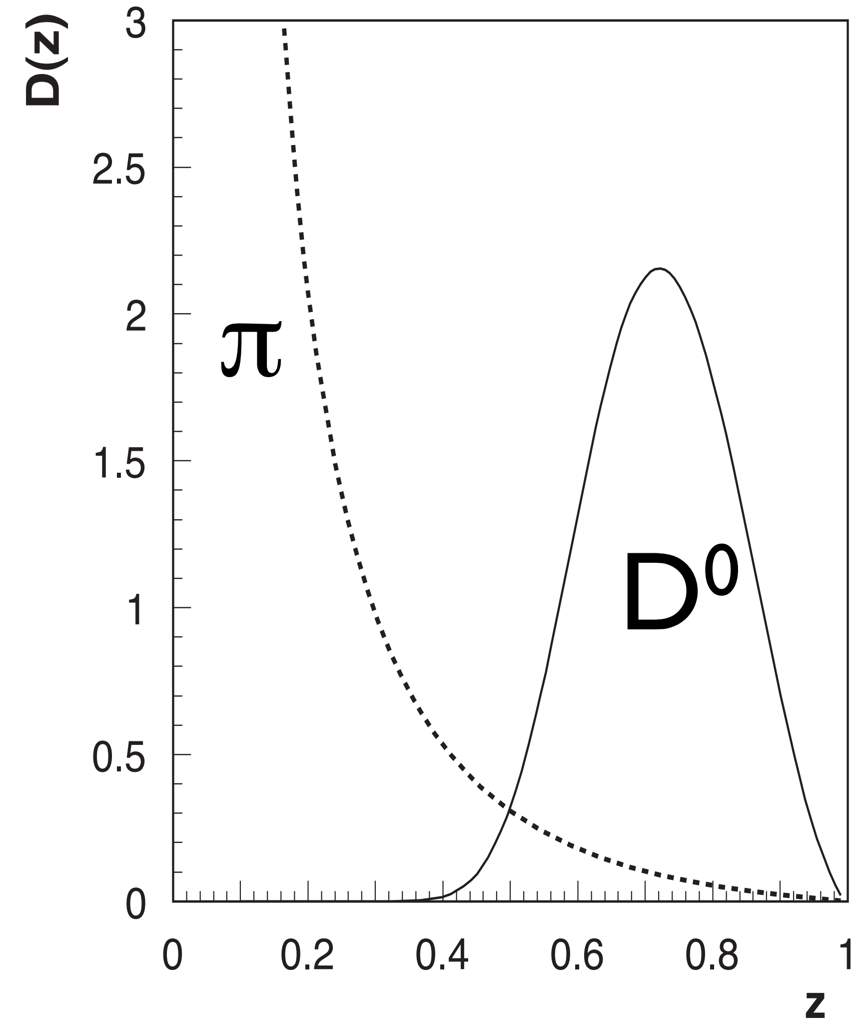


ATLAS results for b-quarks *do* show centrality dependence (μ-tagged open heavy flavor), but similar suppression for central collisions as CMS

ATLAS-CONF-2012-050



Fragmentation functions



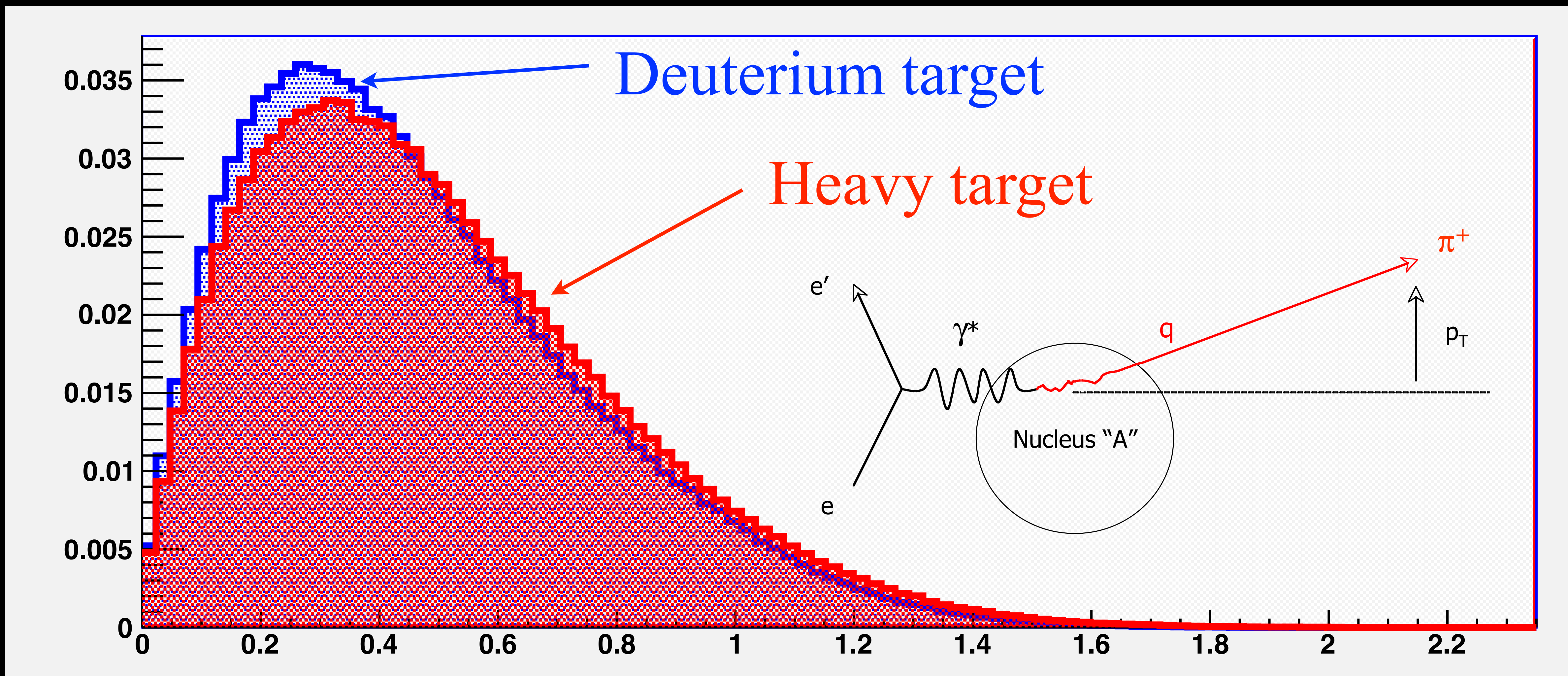
EIC Year 1

Definitive comparisons of light quark and heavy quark energy loss

Access to very strong, unique light quark energy loss signature via D^0 heavy meson. Compare to s and c quark energy loss in D_s^+

Observables: Transverse Momentum Broadening

$$\Delta p_T^2 \equiv \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_D$$

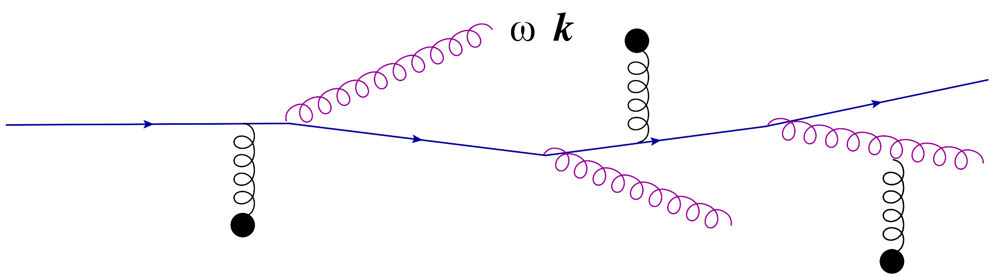


No time to discuss other DIS observables: multi-hadron multiplicity ratios, photon-hadron correlations, Bose-Einstein correlations, spin asymmetries, color transparency, more....

Energy loss induces *additional* p_T broadening

A large radiative correction to $\hat{q}$

- $\hat{q}$: the result of collisions in the medium ... but not only !
- Gluon emissions contribute to momentum broadening, via their recoil !



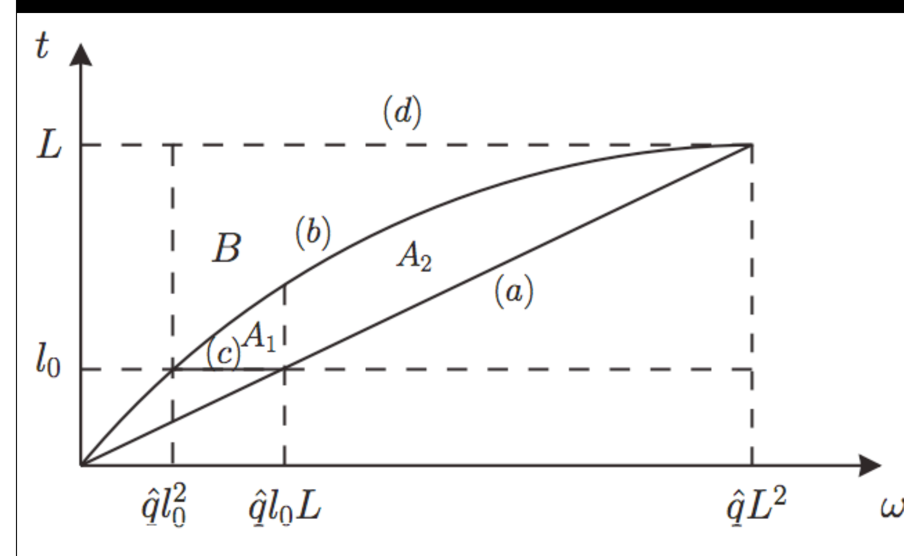
$$\langle p_\perp^2 \rangle_{\rm rad} \sim \int_\omega \int_{\boldsymbol{k}} \boldsymbol{k}^2 \frac{{\rm d}N}{{\rm d}\omega {\rm d}^2\boldsymbol{k}}$$

- Dominant effect from relatively hard emissions (large $k_\perp$), as triggered by a single scattering (Gunion–Bertsch spectrum)

$$\frac{{\rm d}N}{{\rm d}\omega\, {\rm d}^2\boldsymbol{k}} \simeq \frac{\alpha_s}{\omega}\frac{\hat{q}L}{k_\perp^4} \quad\Longrightarrow\quad \langle p_\perp^2\rangle_{\rm rad} \sim L\,\alpha_s\hat{q}\int\frac{{\rm d}\omega}{\omega}\int\frac{{\rm d}k_\perp^2}{k_\perp^4} \equiv L\,\Delta\hat{q}$$

- Formally NLO but enhanced by a double-log *(Liou, Mueller, Wu, 13)*

$$\frac{\Delta\hat{q}}{\hat{q}} \simeq \frac{\alpha_s N_c}{2\pi}\ln^2(LT) \simeq 0.75 \ (!) \Longrightarrow \text{need for resummation}$$



$$\langle p_\perp^2\rangle = \frac{\alpha_s N_c}{4\pi}\hat{q}L\ln^2\left(\frac{L}{l_0}\right)^2.$$

Double log enhancement: ~**doubles** the amount of broadening seen, both hot and cold matter. Effect may be visible in CLAS data, see later slides

Tseh Liou, A.H. Mueller, Bin Wu, http://arxiv.org/abs/1304.7677

p_T broadening is a tool to sample the gluon field using a colored probe

$$\Delta p_T^2 \propto G(x, Q^2)\rho L$$

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http://arxiv.org/abs/1205.5741 ,http://arxiv.org/abs/hep-ph/0006326,

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  p_T broadening directly samples the gluon field

  is sensitive to (or equal to) the saturation scale

p_T broadening is a tool to sample the gluon field using a colored probe

$$\Delta p_T^2 \propto G(x, Q^2)\rho L$$

- Universal result in perturbative calculations

http://arxiv.org/abs/1205.5741 ,http://arxiv.org/abs/hep-ph/0006326,

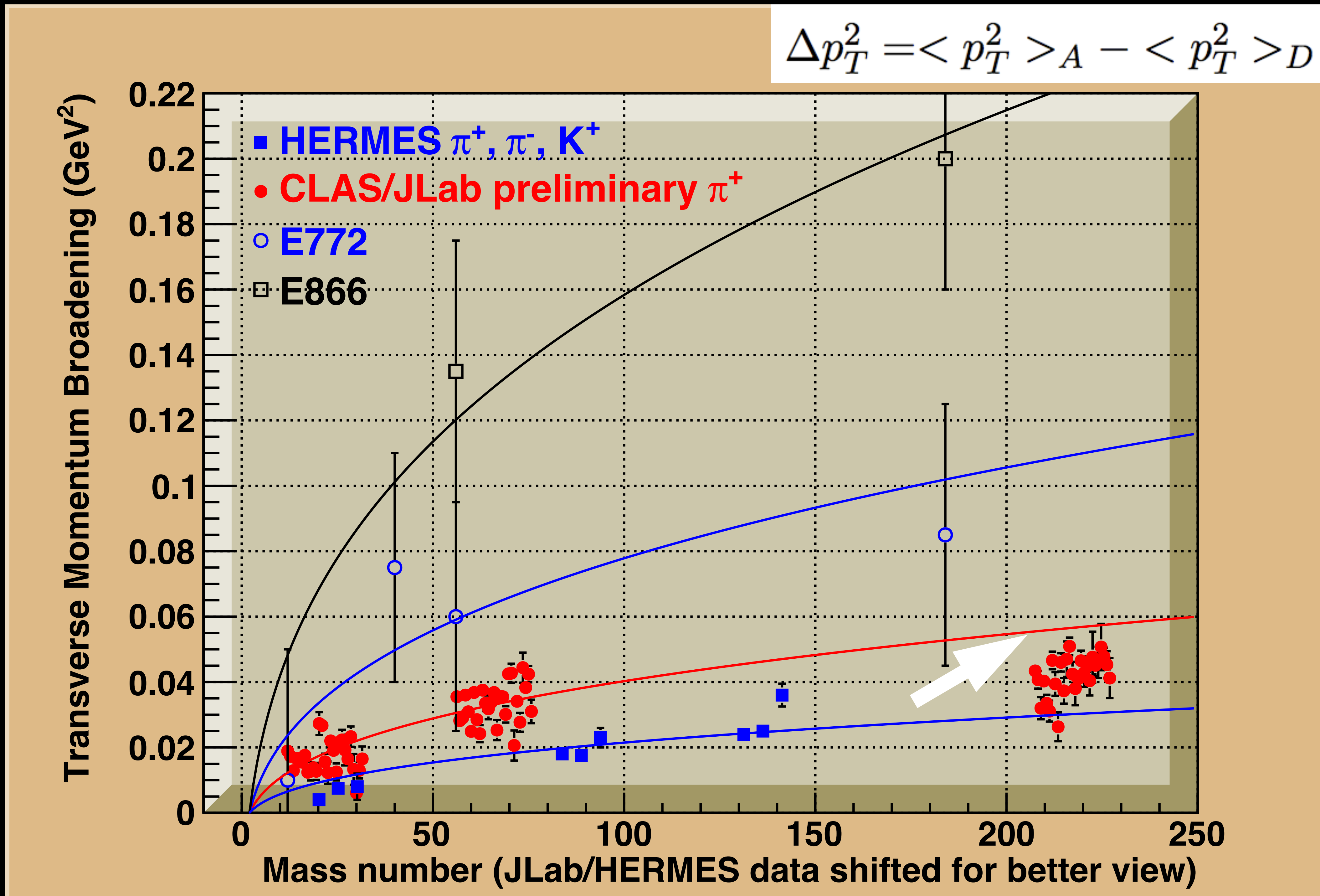
http://arxiv.org/abs/1208.0751, etc

p_T broadening directly samples the gluon field

is sensitive to (or equal to) the saturation scale

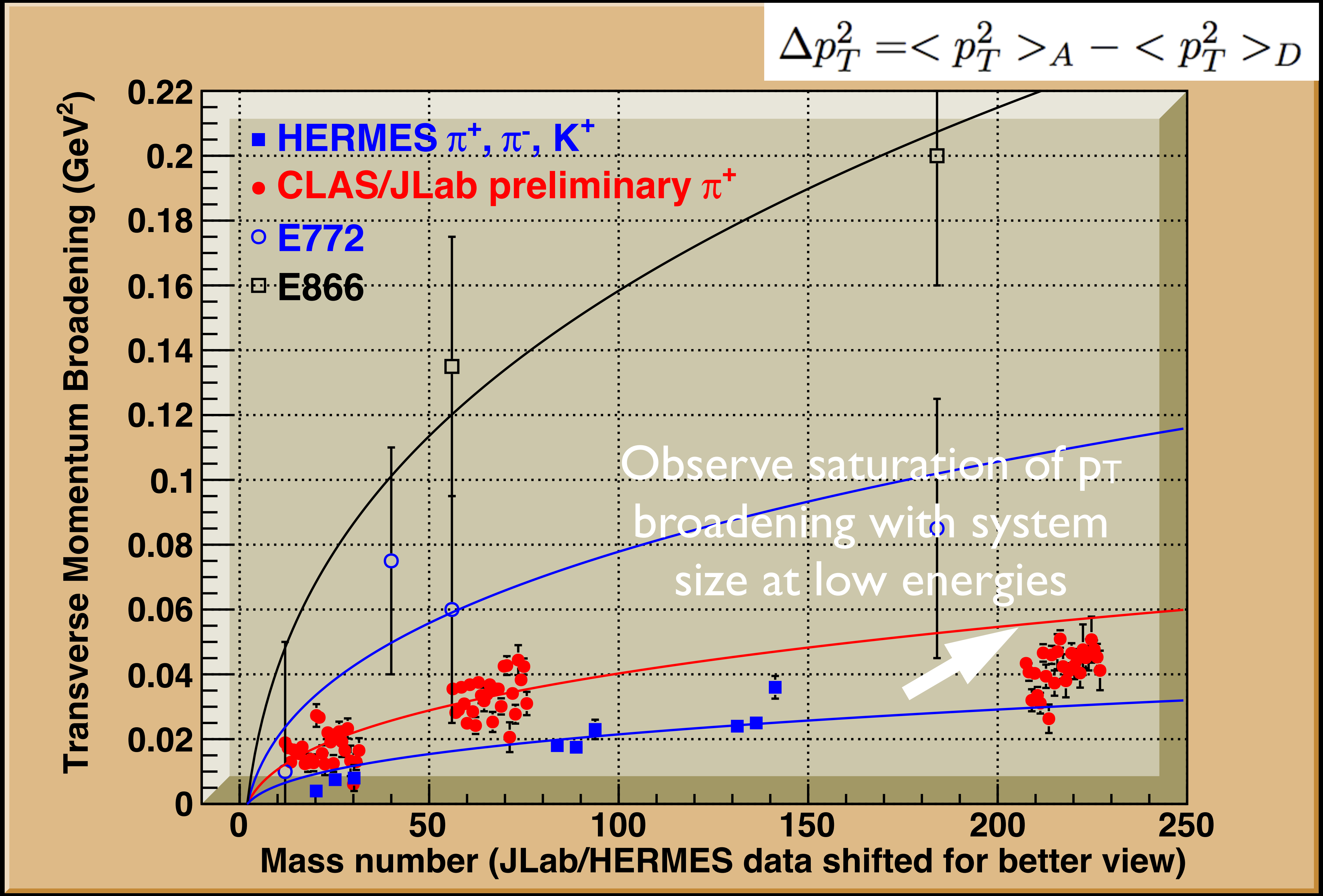
http://arxiv.org/abs/1001.4281

p_T broadening data - Drell-Yan and DIS



- New, precise data with identified hadrons!
- CLAS π^+: 81 four-dimensional bins in Q^2, ν, z_h, and A
- Intriguing *saturation*: production length or something else?

p_T broadening data - Drell-Yan and DIS



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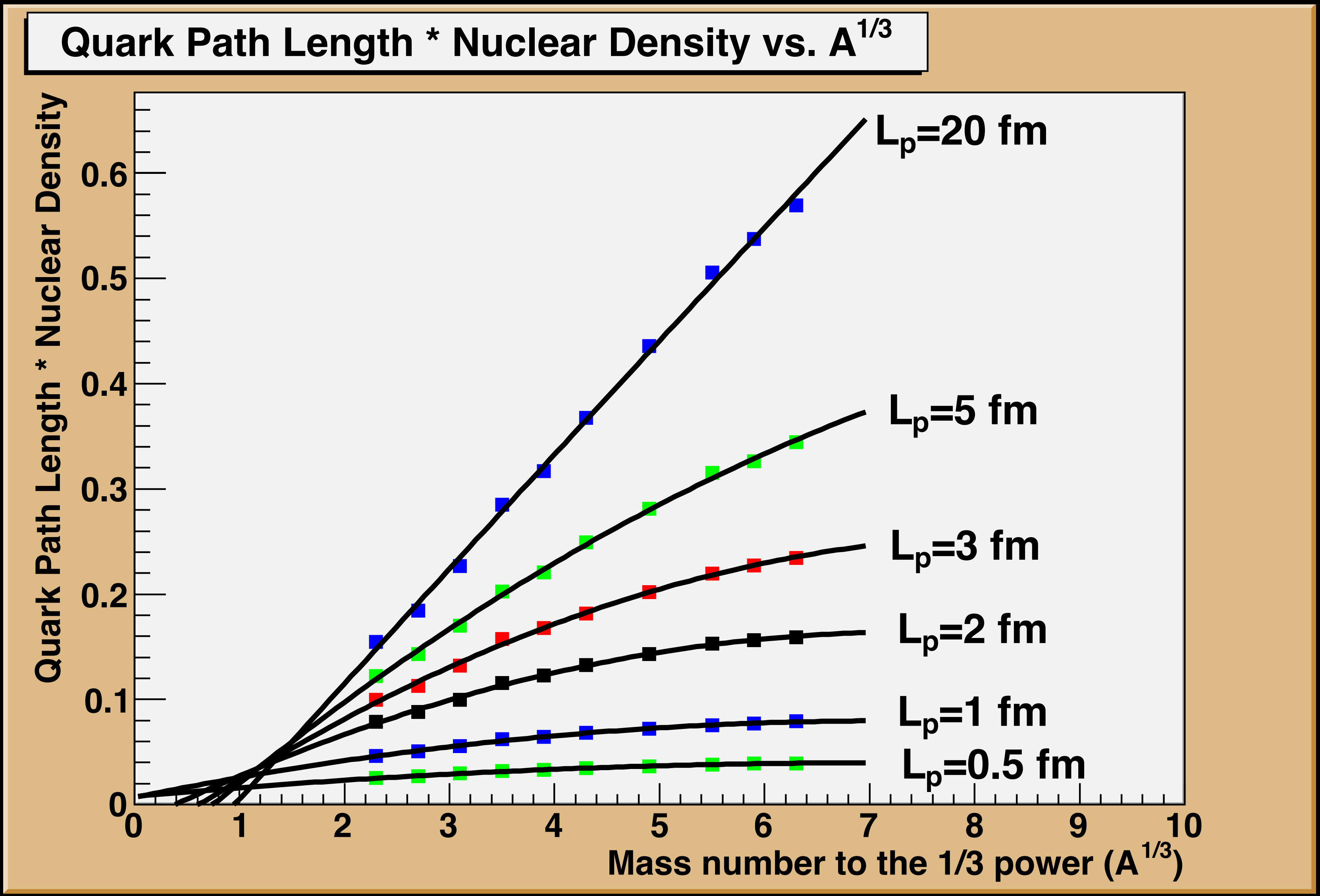
Production Time Extraction: Geometrical Interpretation

1) Assume saturation is due to shorter production length ℓ : then can *measure* ℓ



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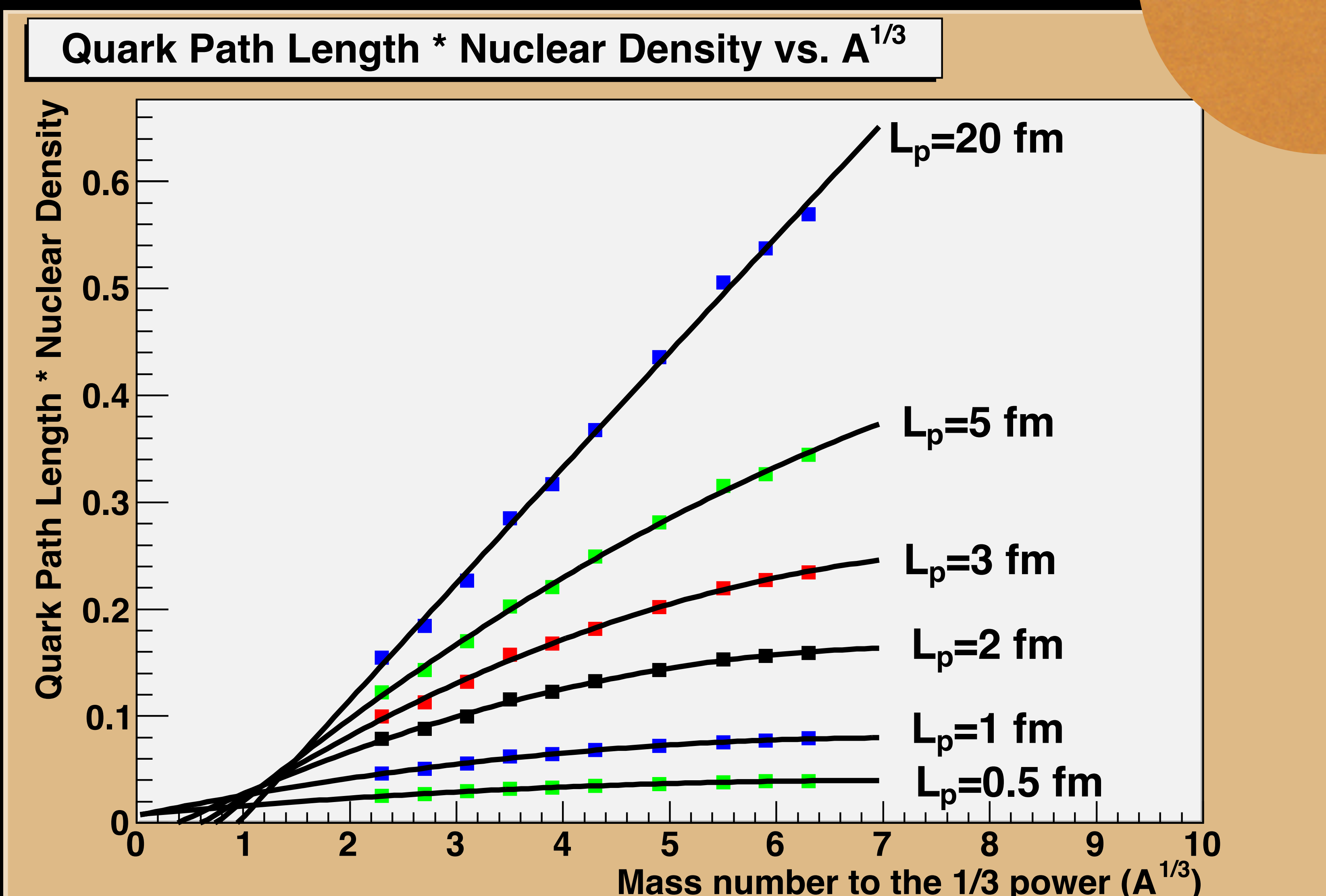

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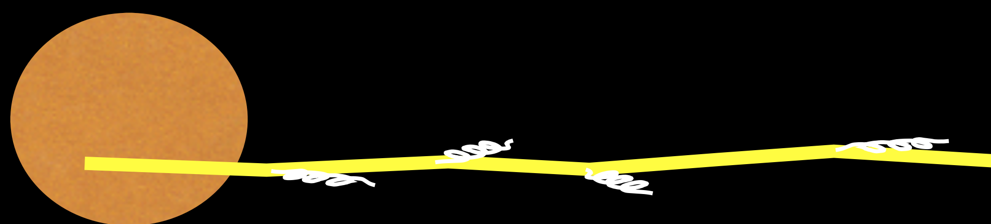

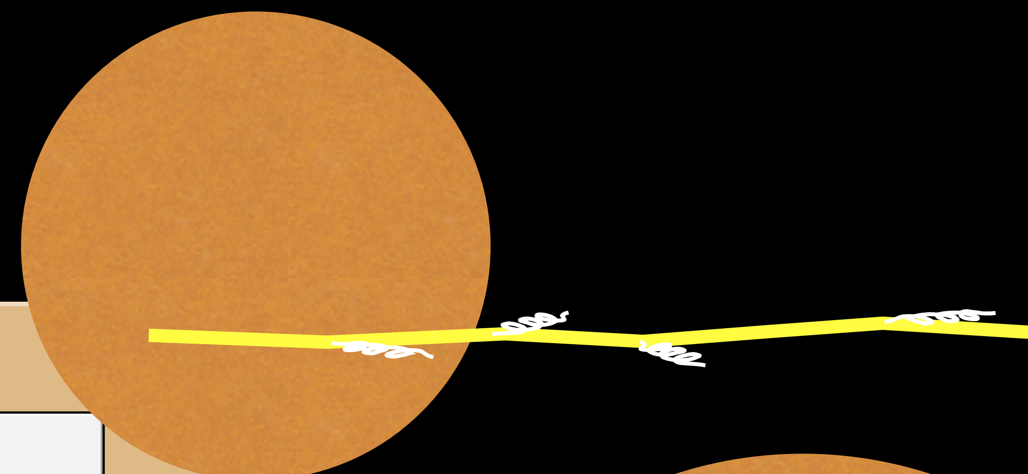

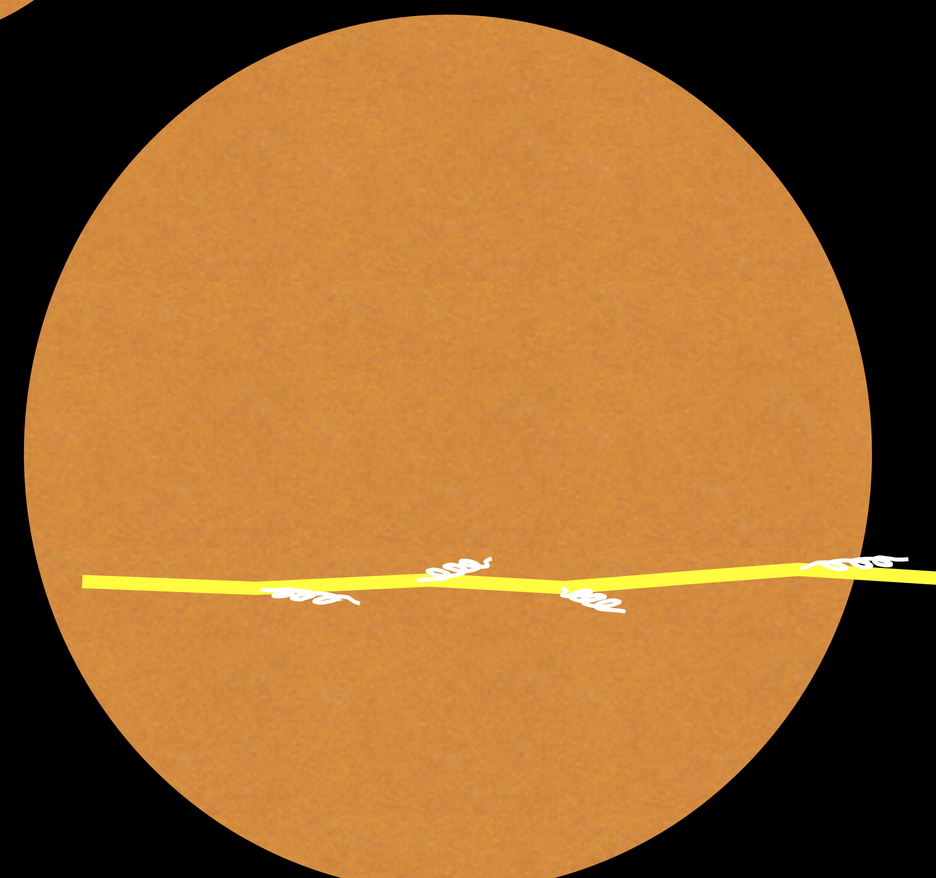

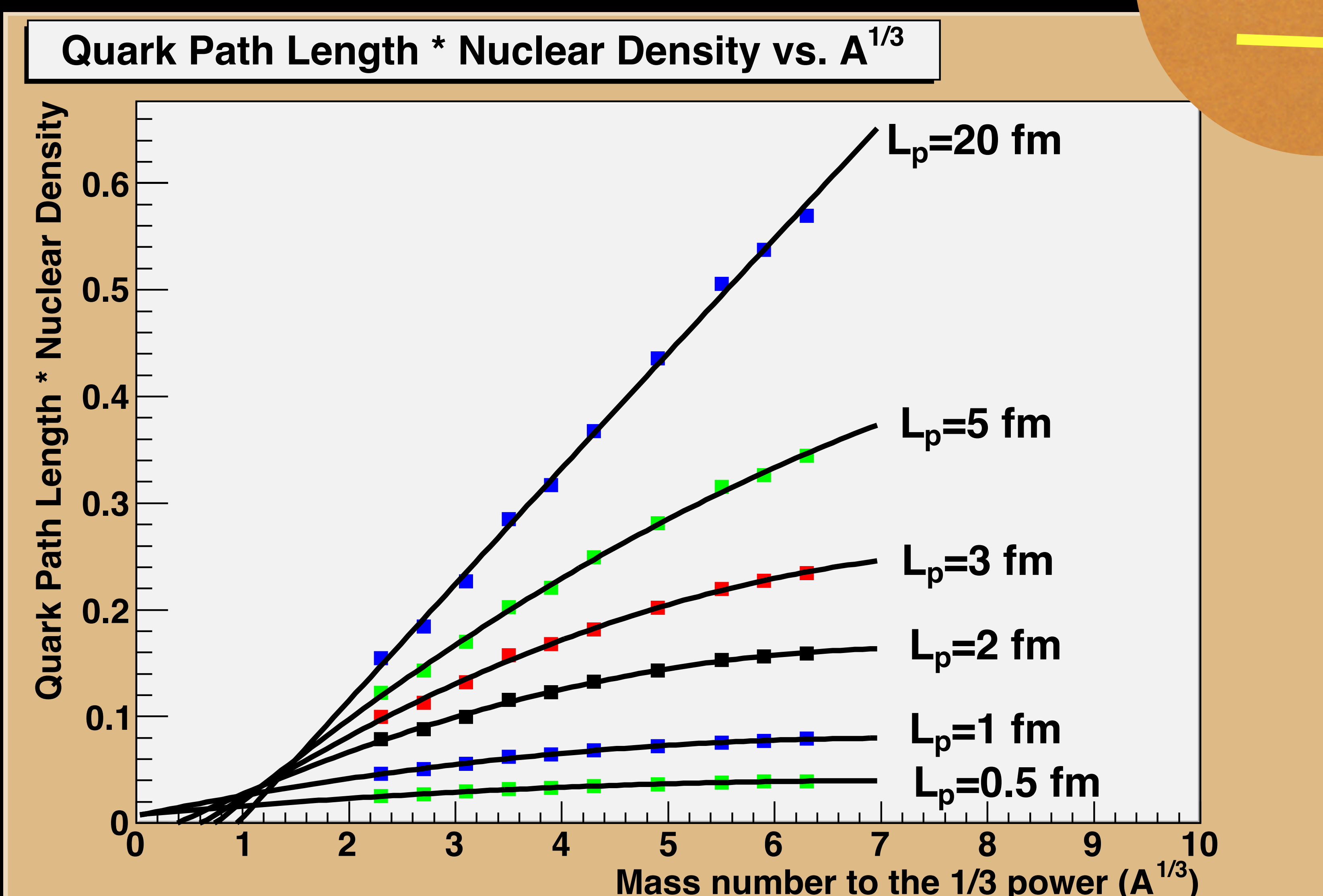

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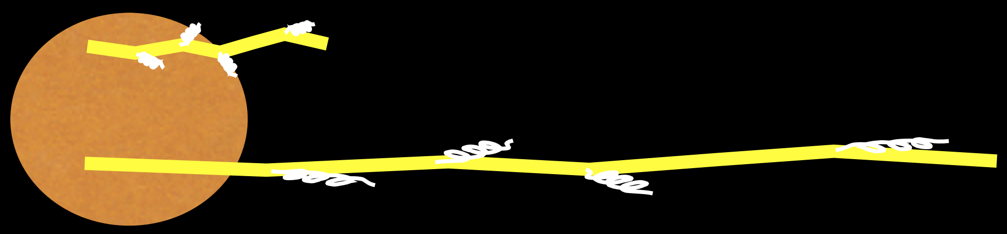

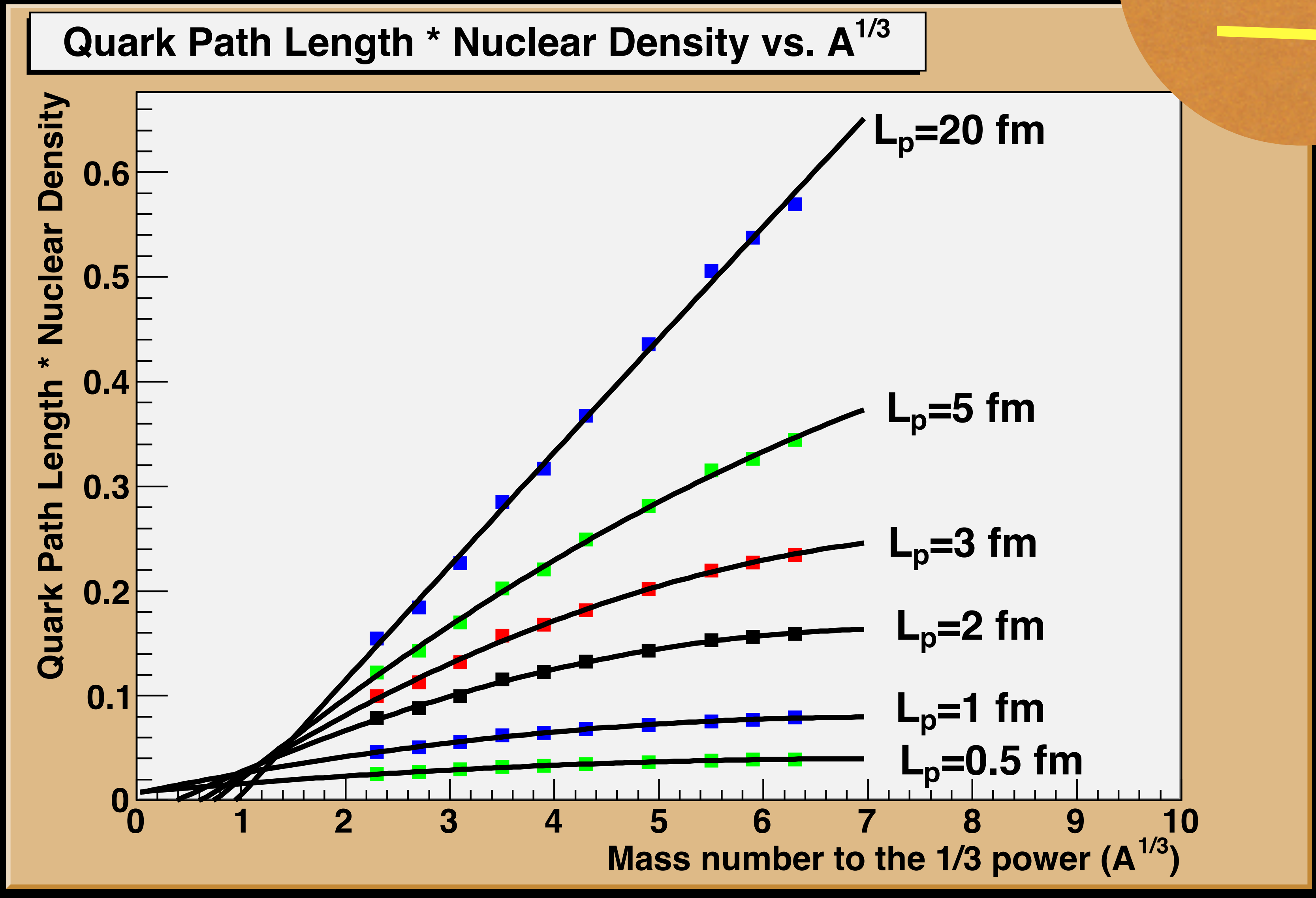

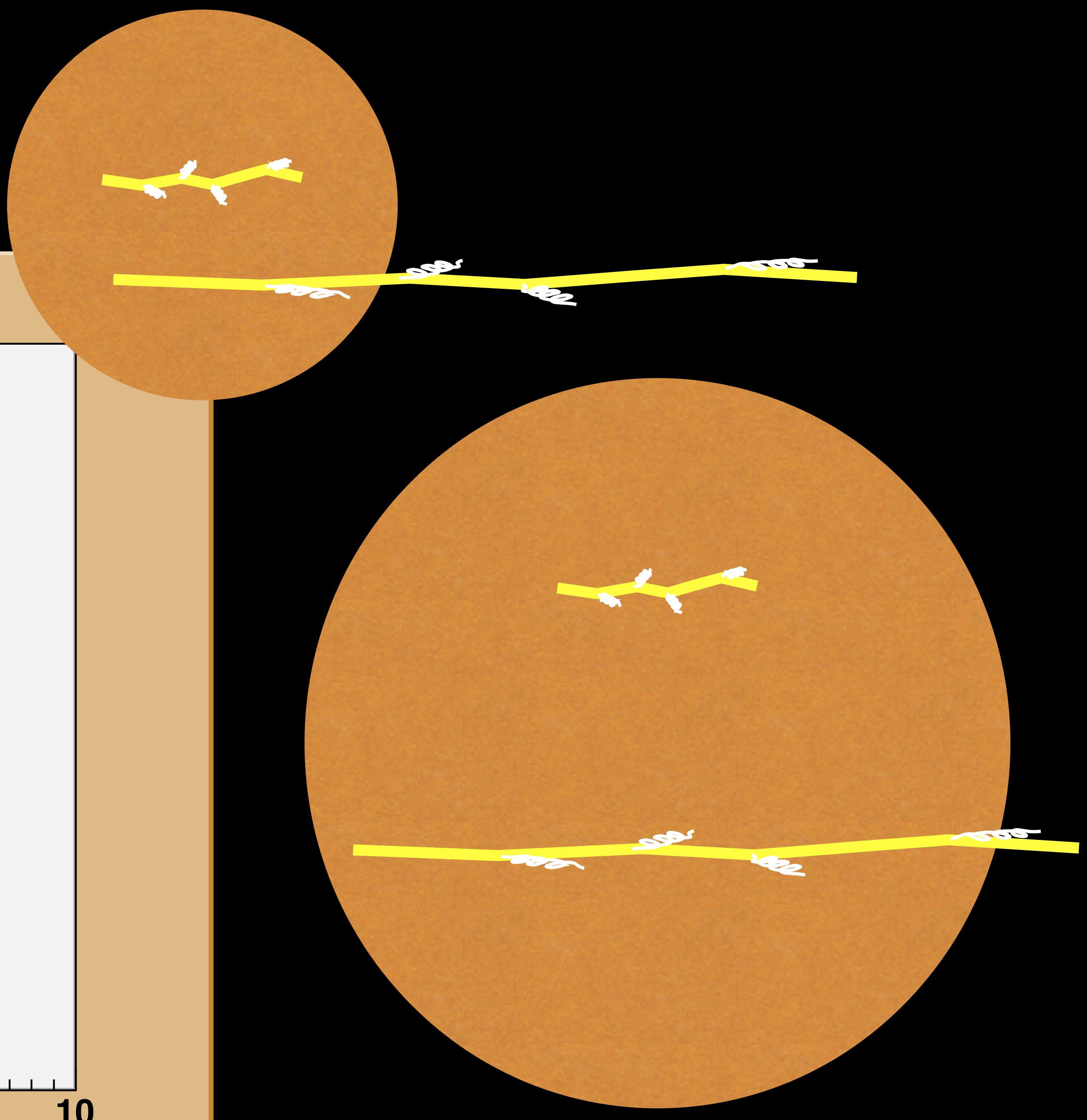

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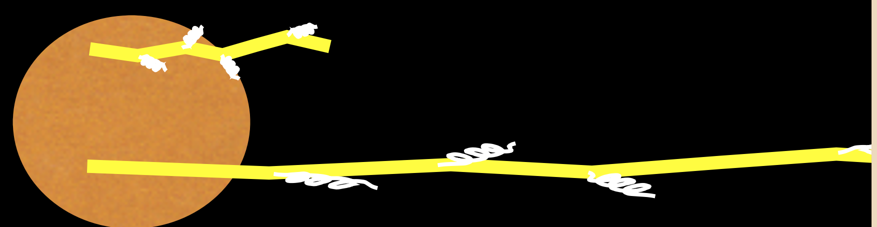
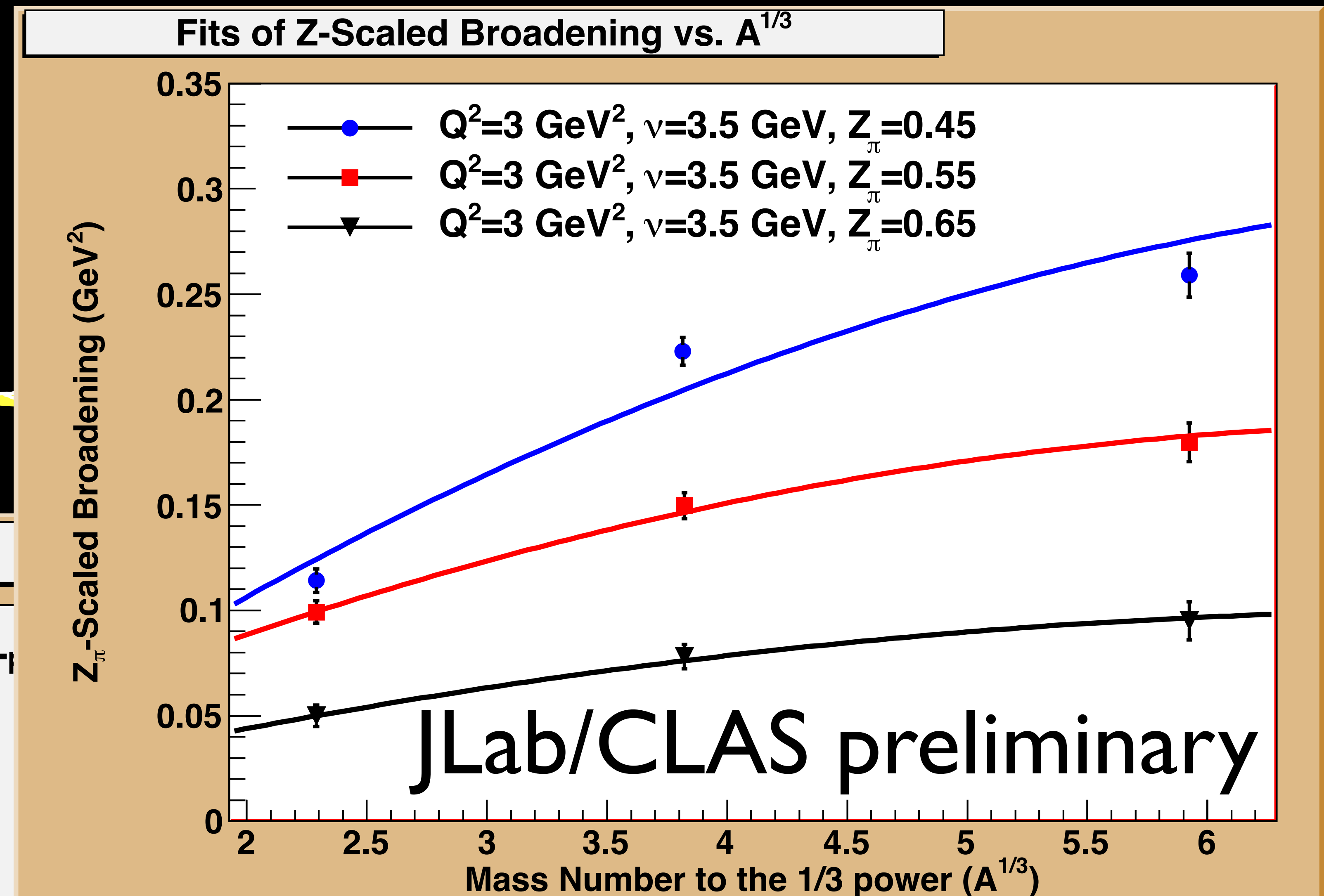
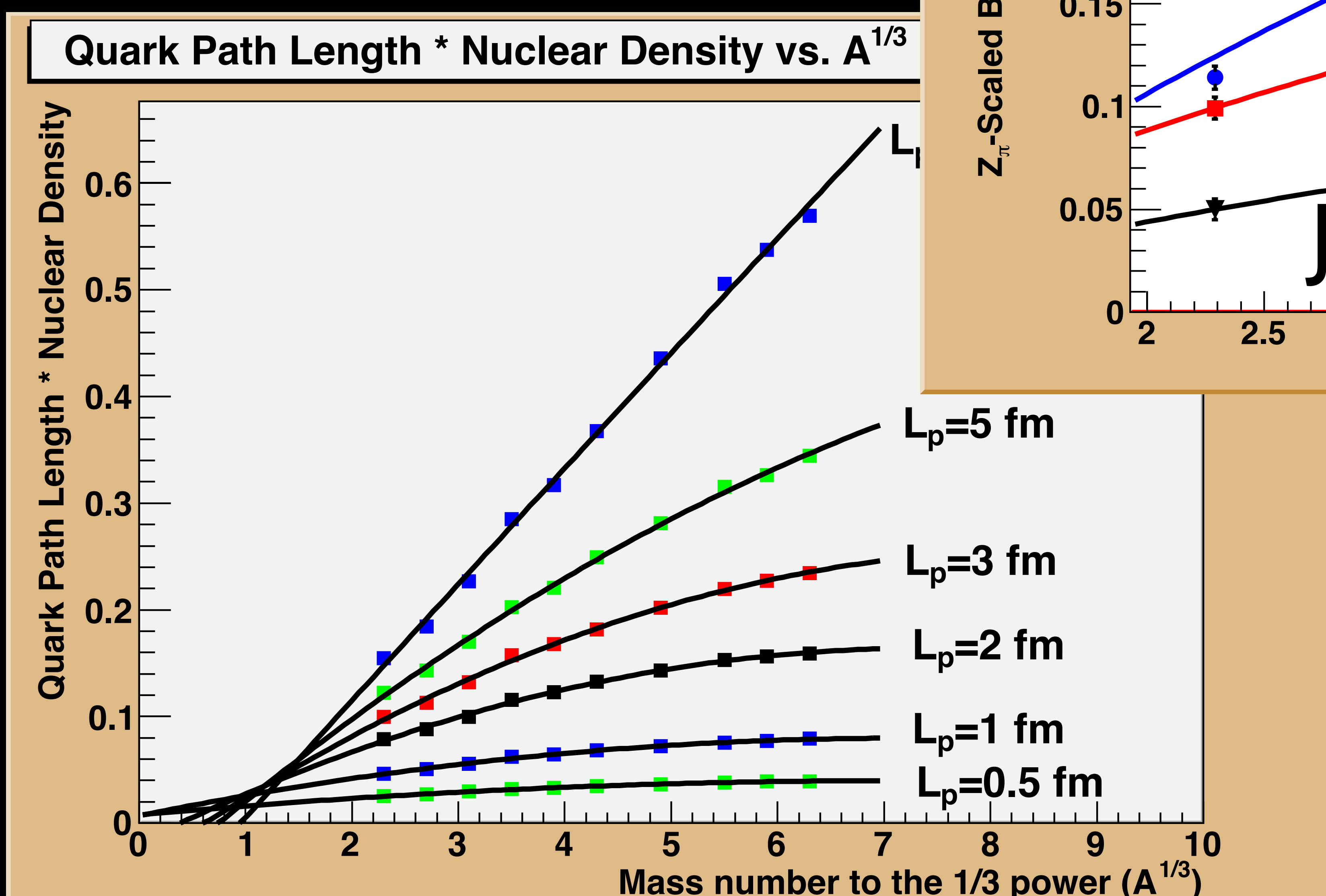
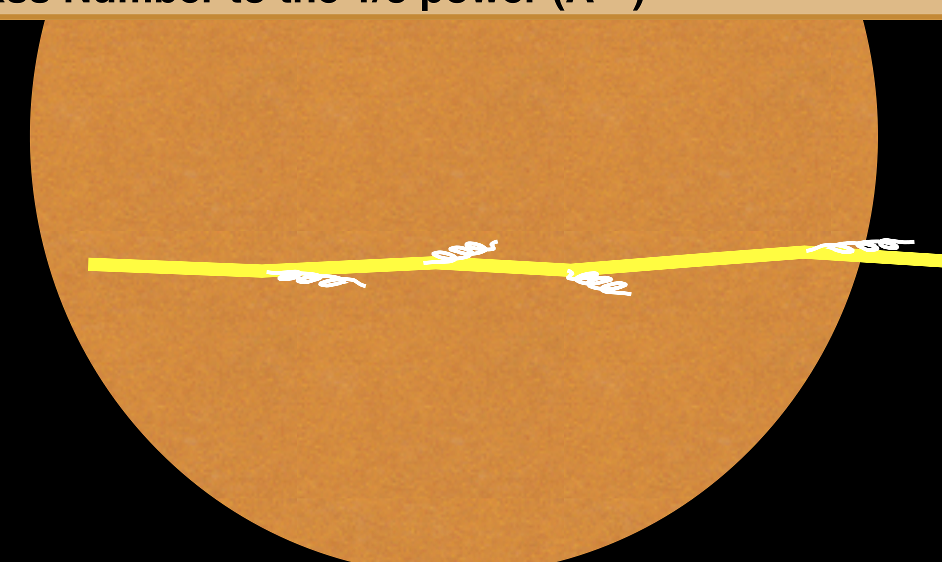


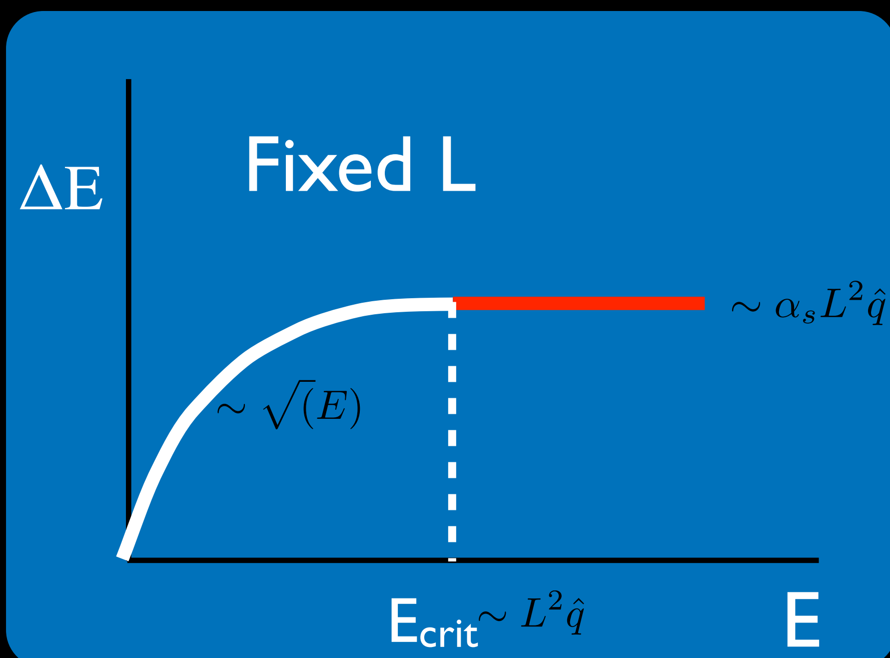






Quark dE/dx effects

2) Assume saturation is due to two effects: (a) dE/dx behavior *plus* (b) stimulation of additional broadening by gluon emission



$$E_{crit} \approx 0.4 \cdot (\frac{L}{1\ fm})^2\ \ GeV$$

	Carbon	Iron	Lead
E_{crit} (GeV)	2.5	7.1	17
<ΔE> ratio to C	1	1.8	2.8

The two mechanisms (time dialation and dE/dx effects) will be separable with EIC

EIC ? Year 1

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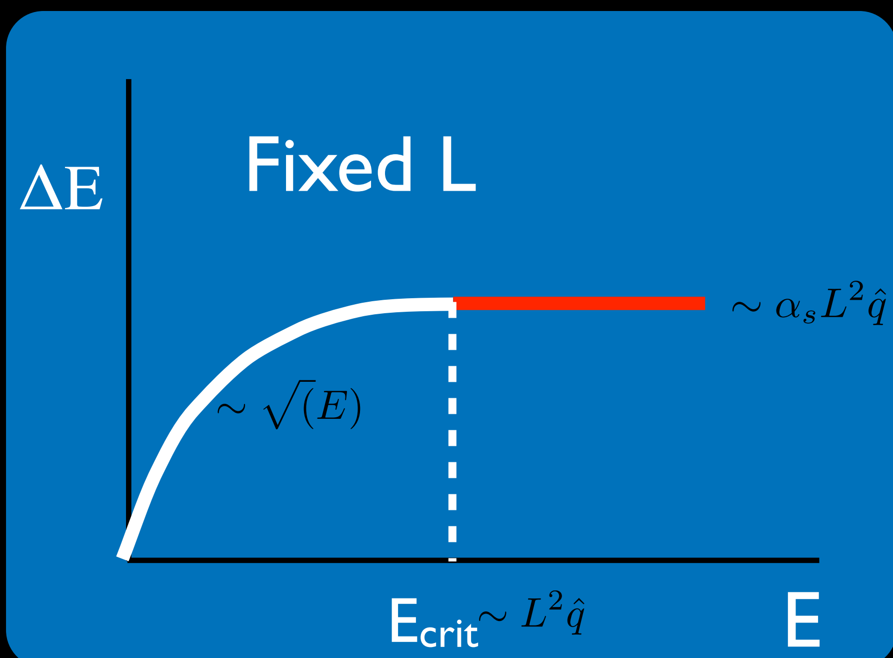

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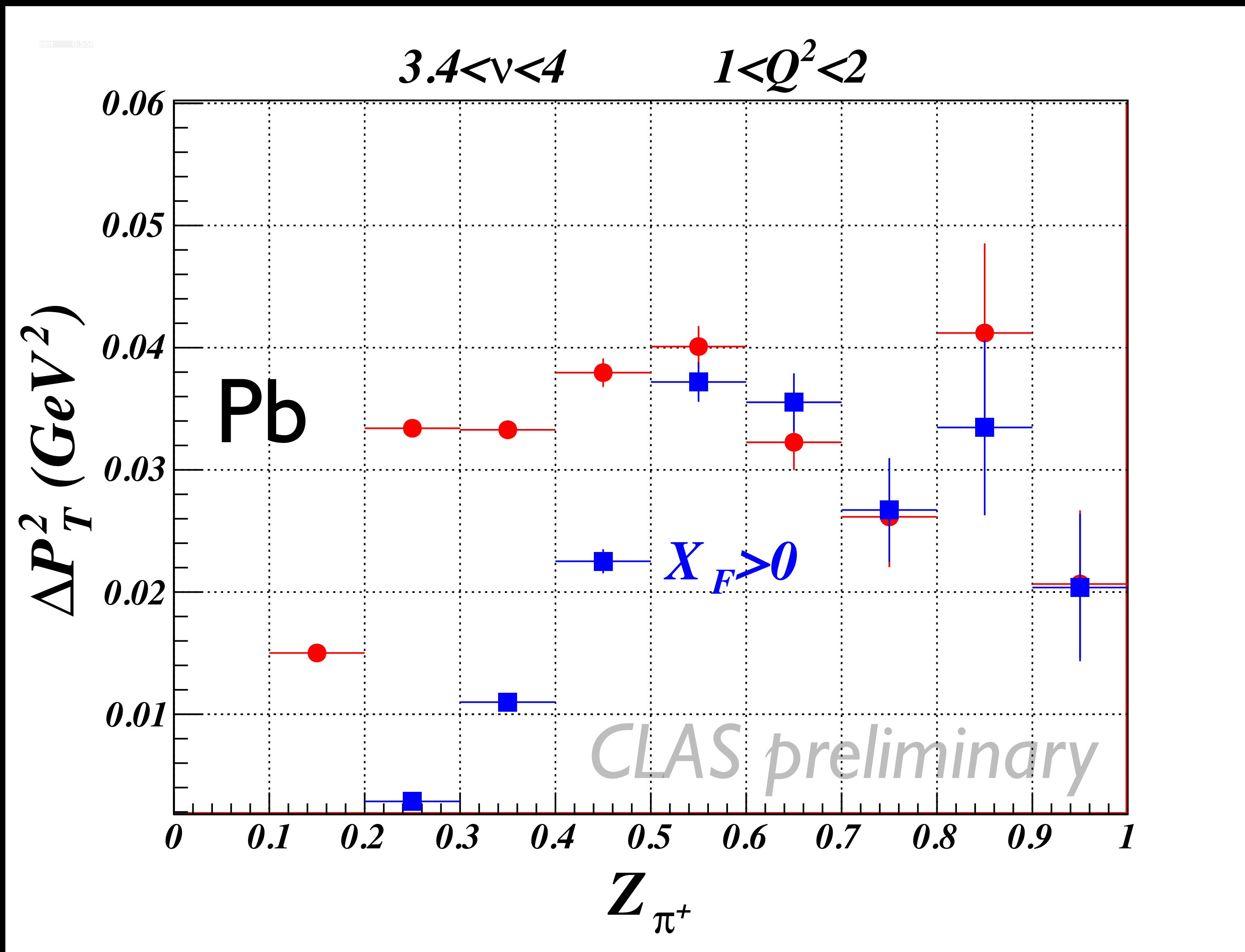
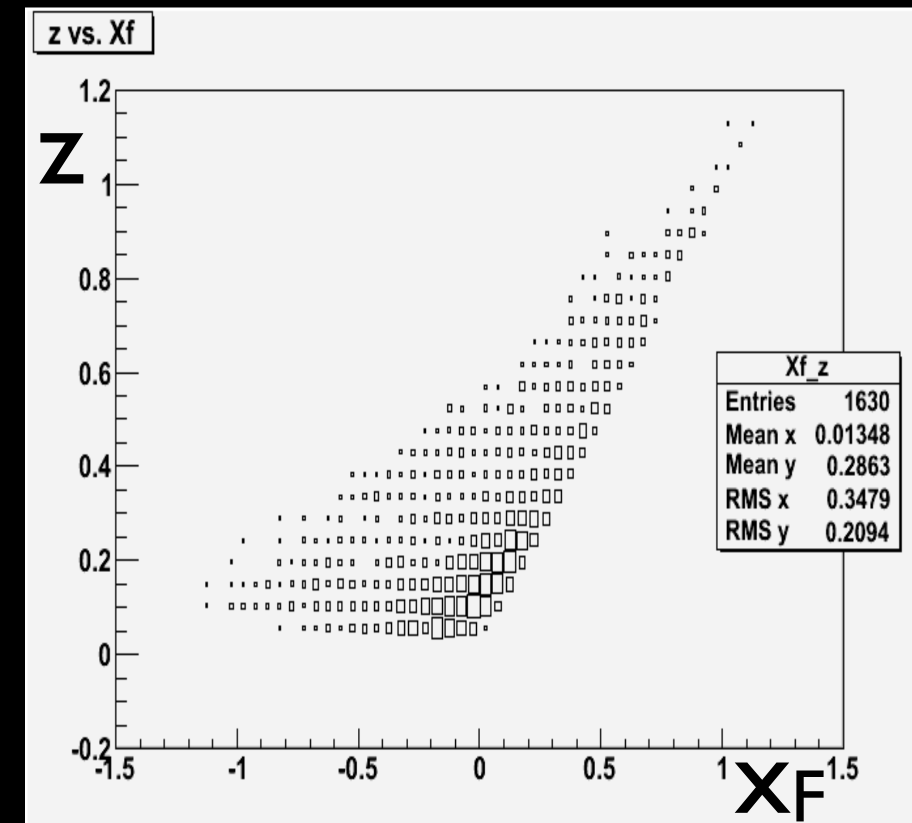
Dependence of p_T broadening on Feynman x





- x_F and z_h are partially correlated

- Feynman x is the fraction ${}^{\pi}p_L/\max\{{}^{\pi}p_L\}$ in the γ^*-N CM system
- Emphasizes current ($x_F>0$) vs. target ($x_F<0$) fragmentation
- First observation that *p_T broadening originates in both regimes*

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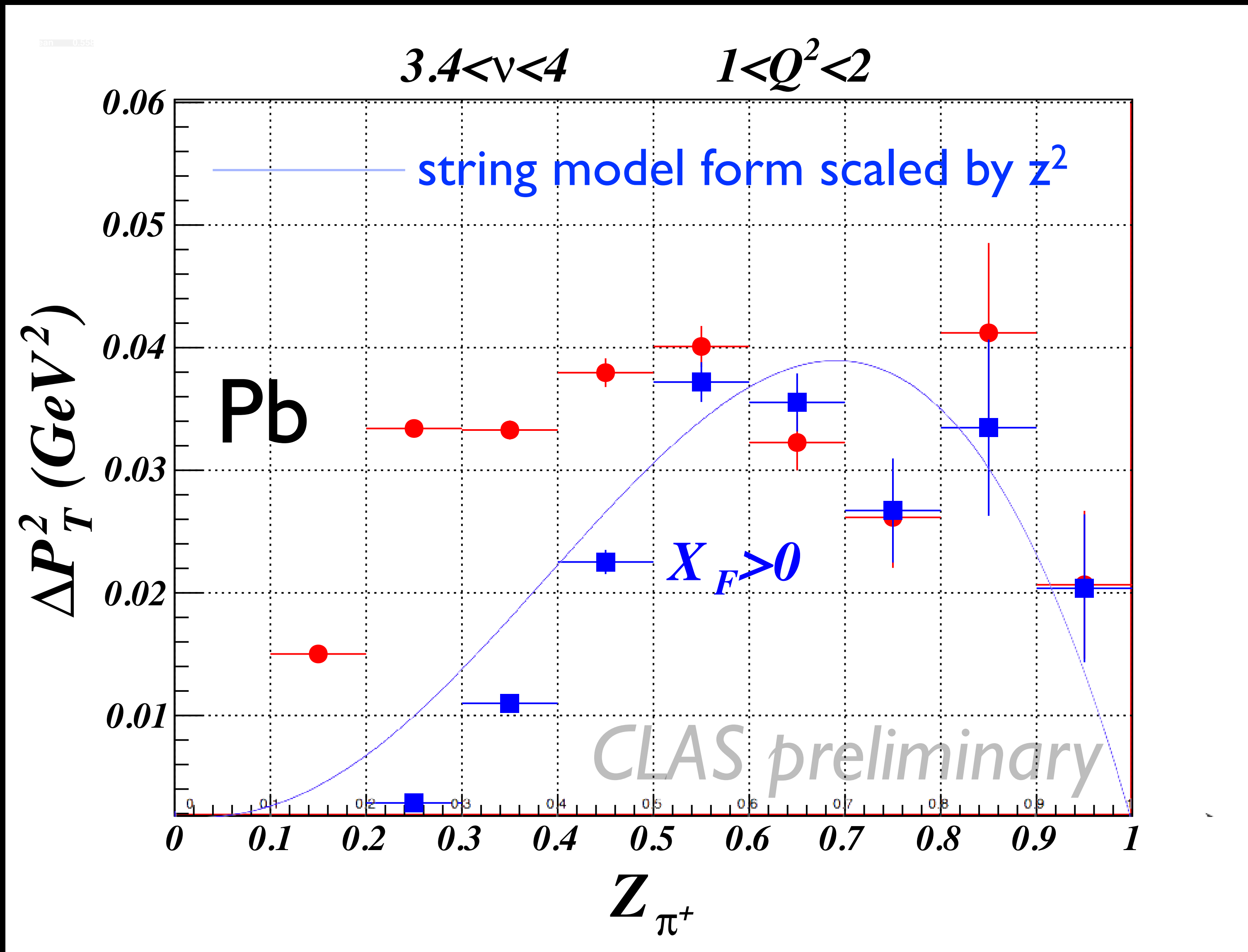

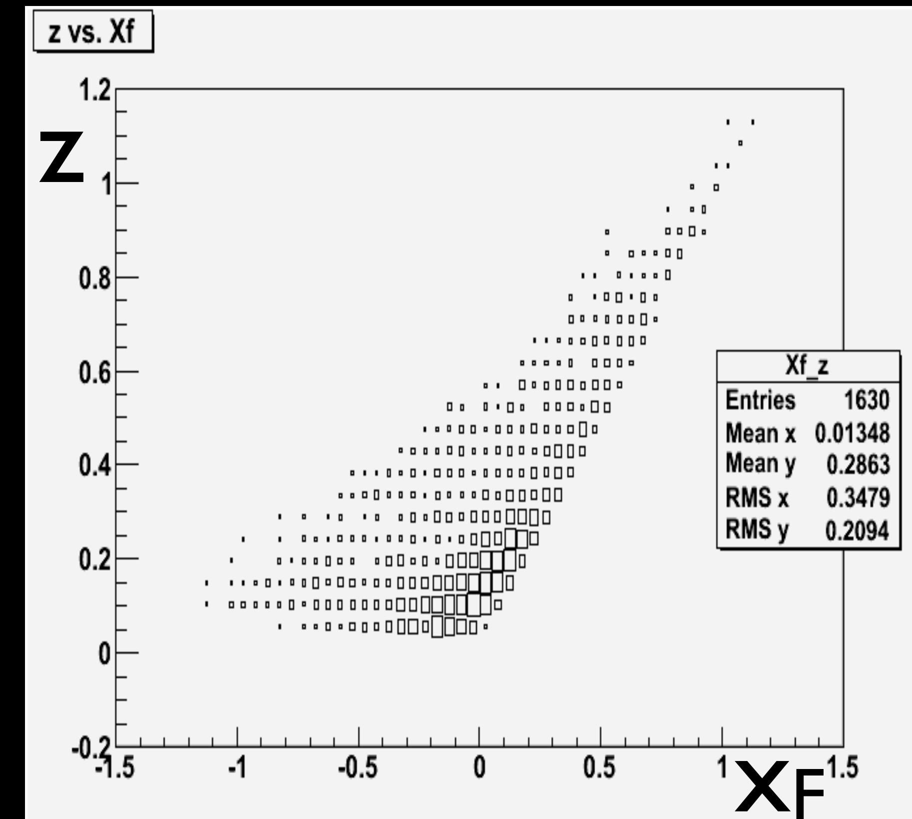

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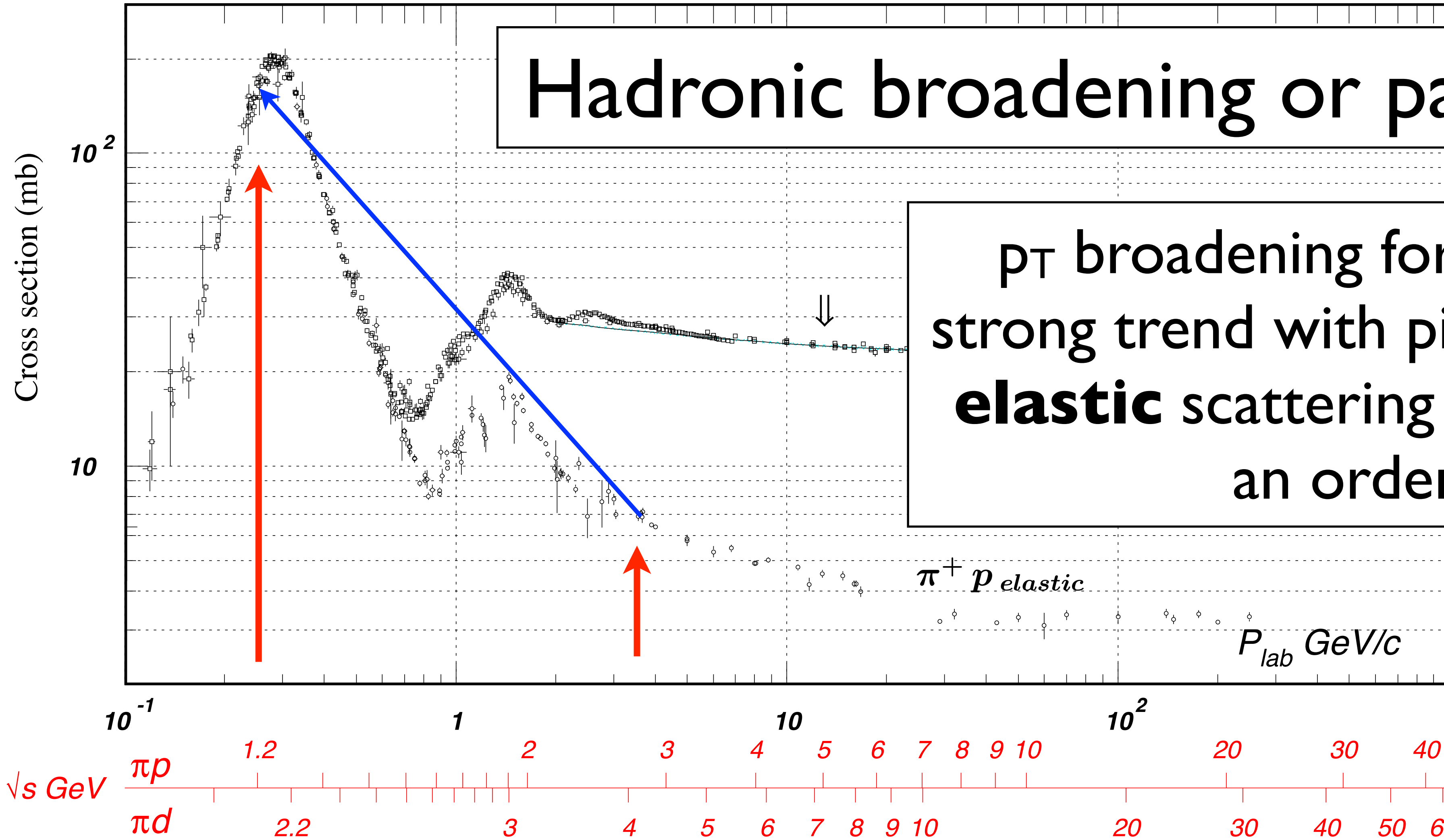
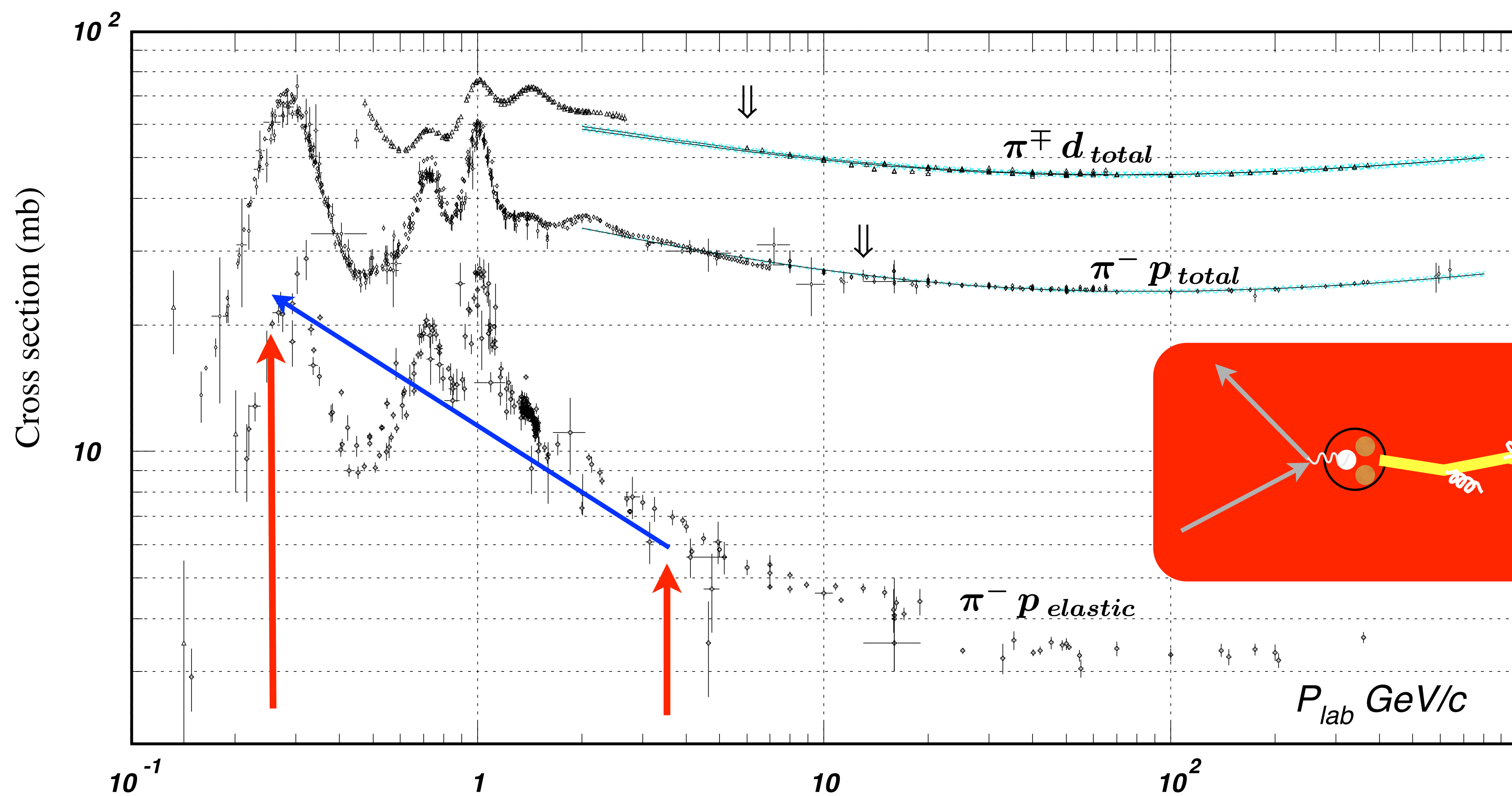
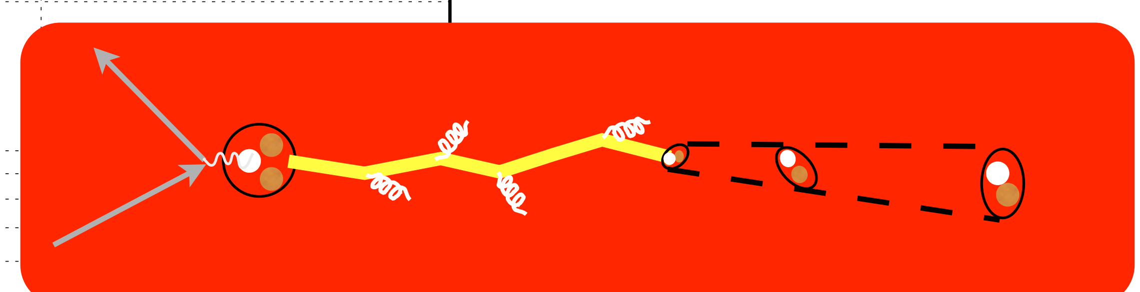
Hadronic broadening or partonic broadening?

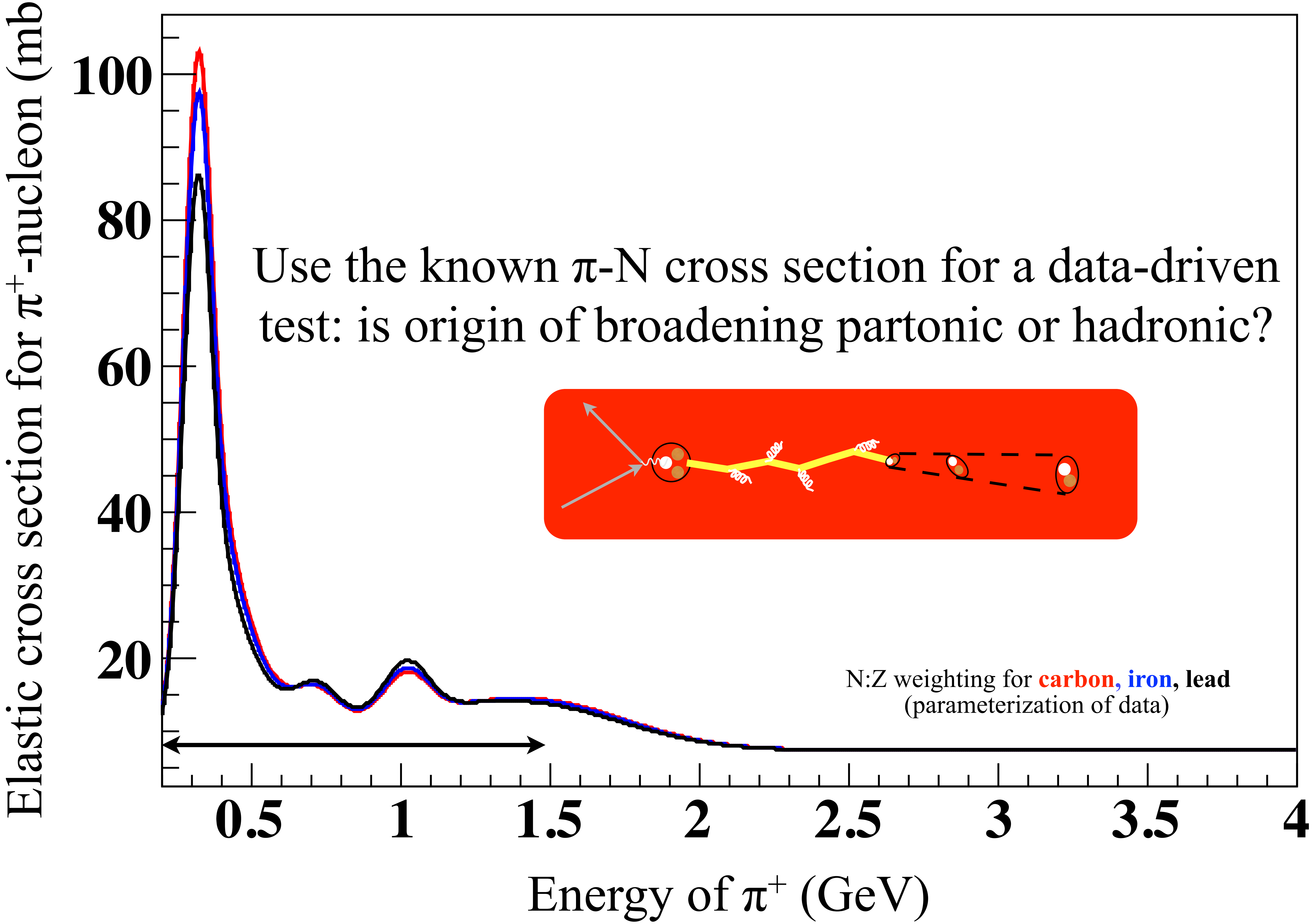
p_T broadening for Pb does not show any strong trend with pion energy, while hadronic **elastic** scattering cross section changes by an order of magnitude



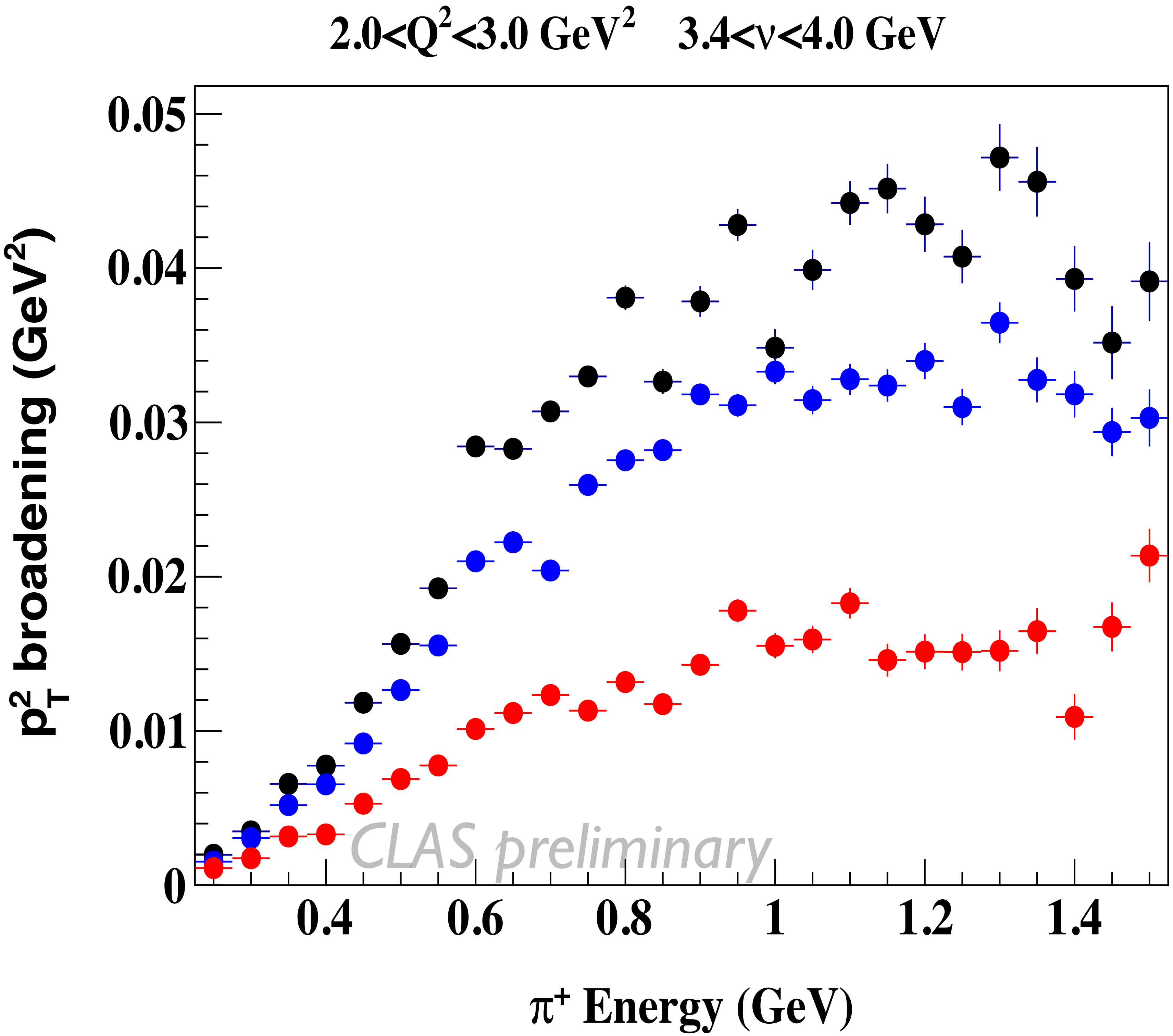




Elastic cross section for π^+-nucleon



p_T^2 Broadening vs. Hadron Energy



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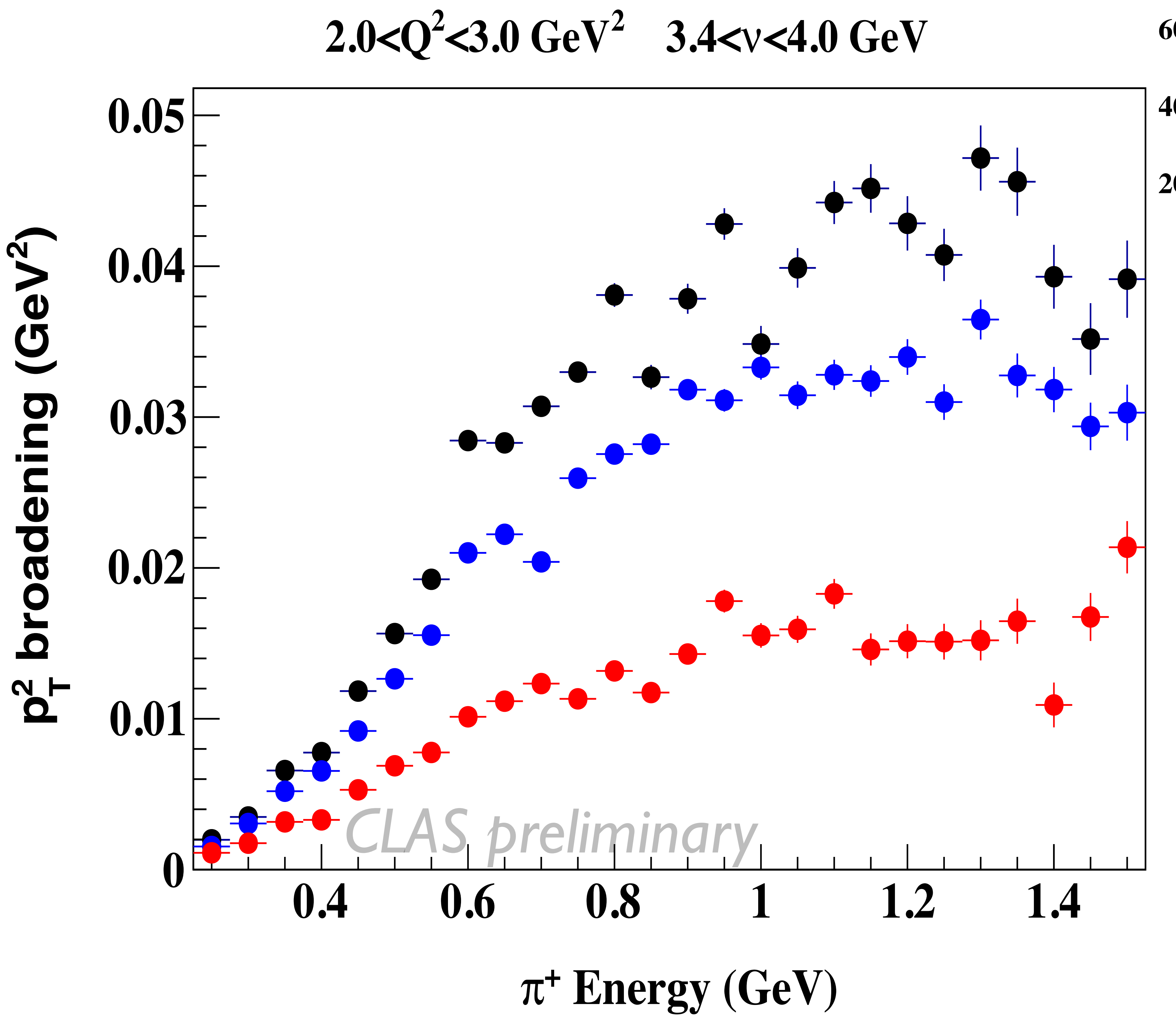

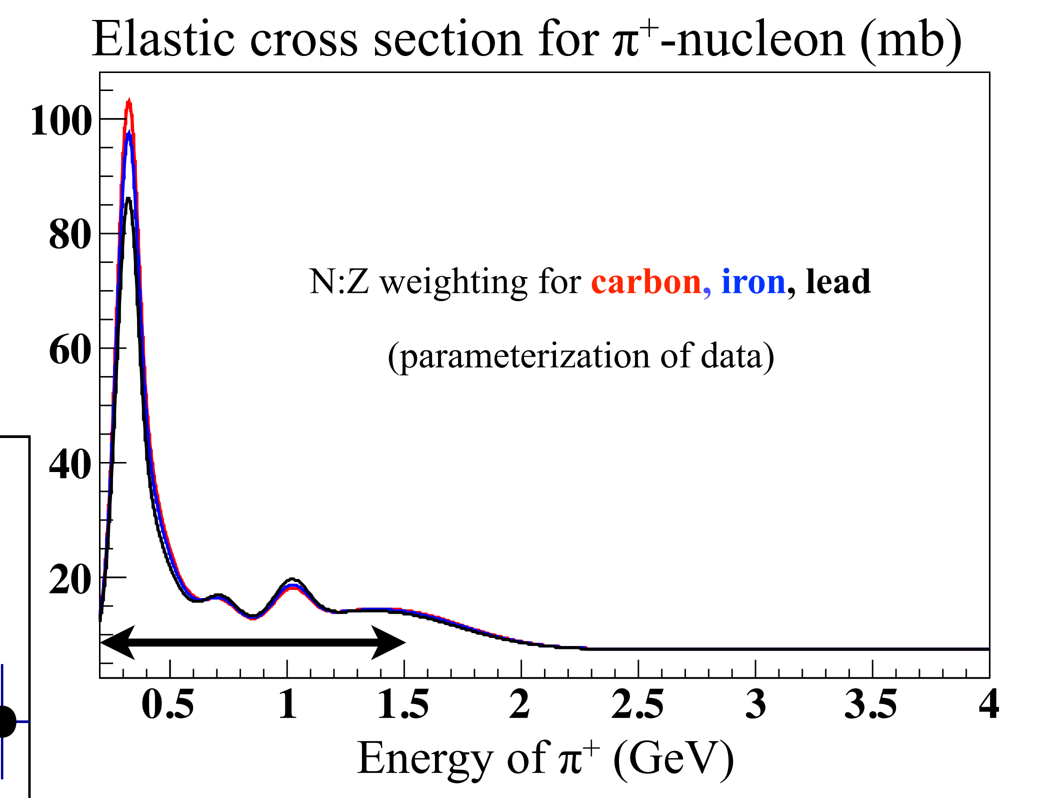

EIC Year 1

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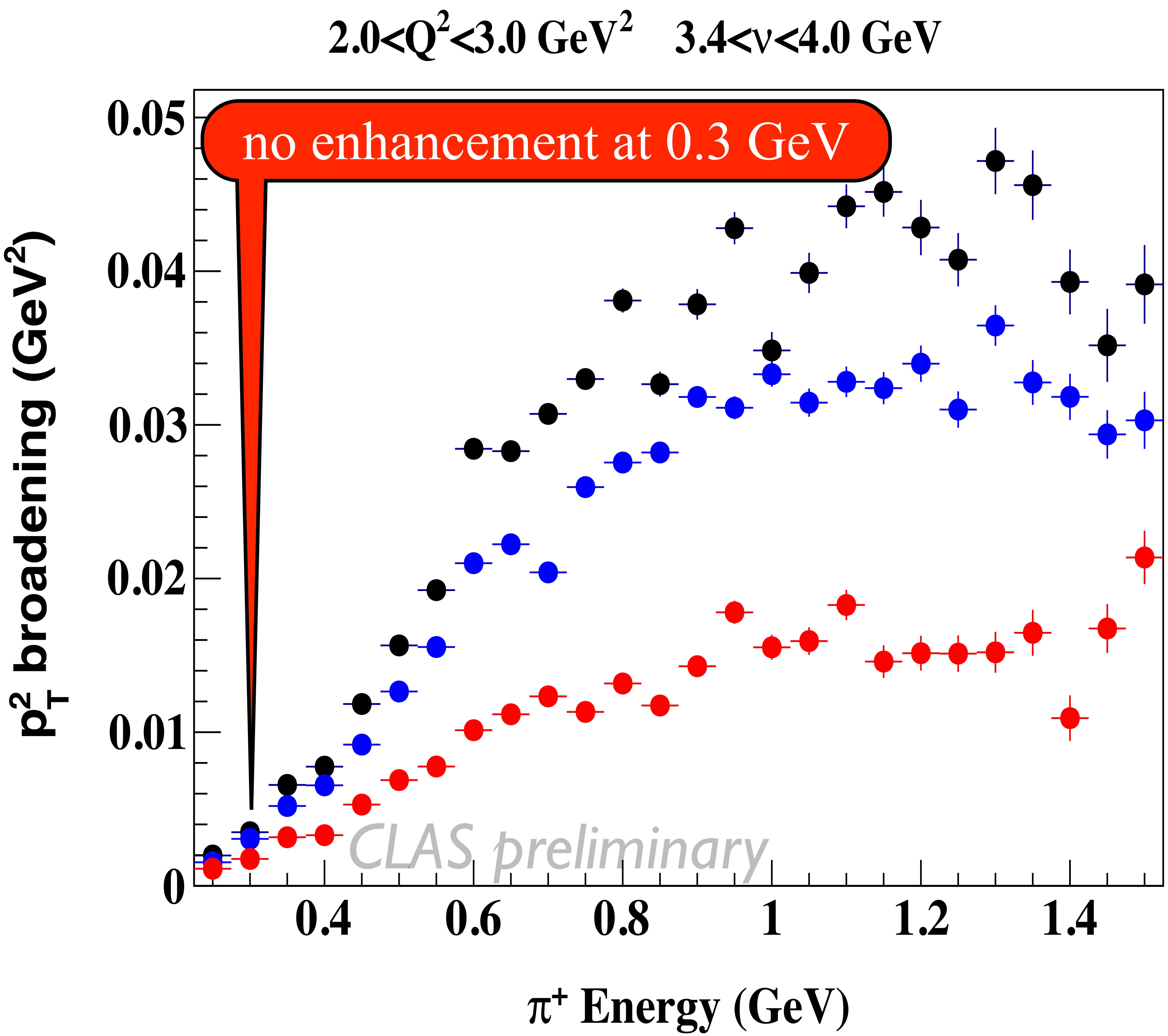

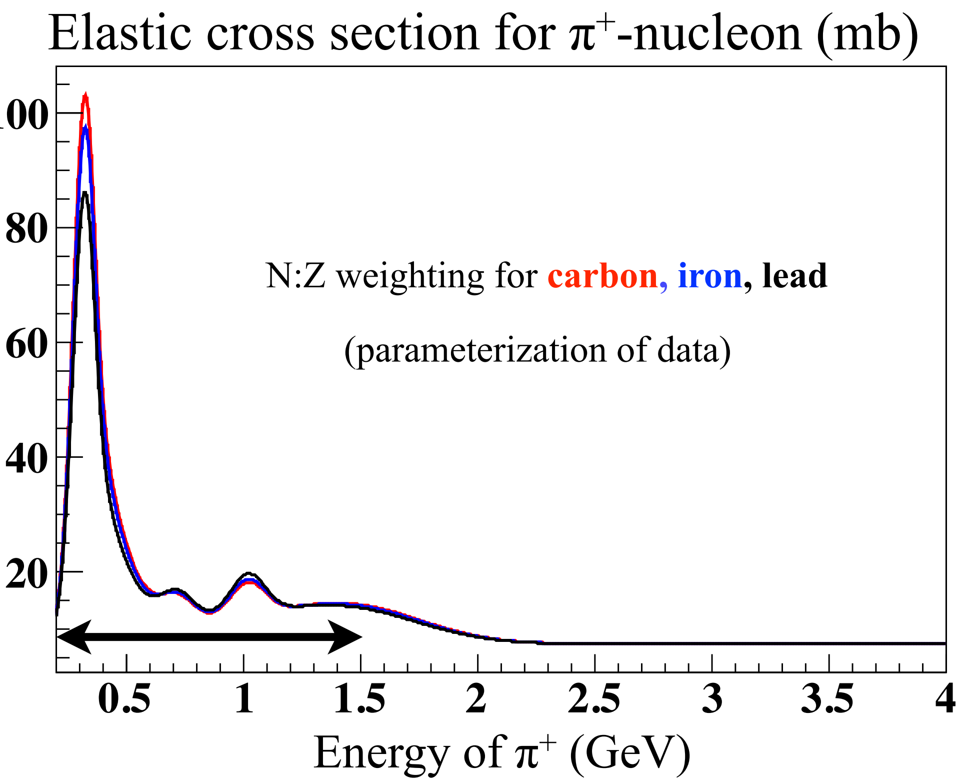

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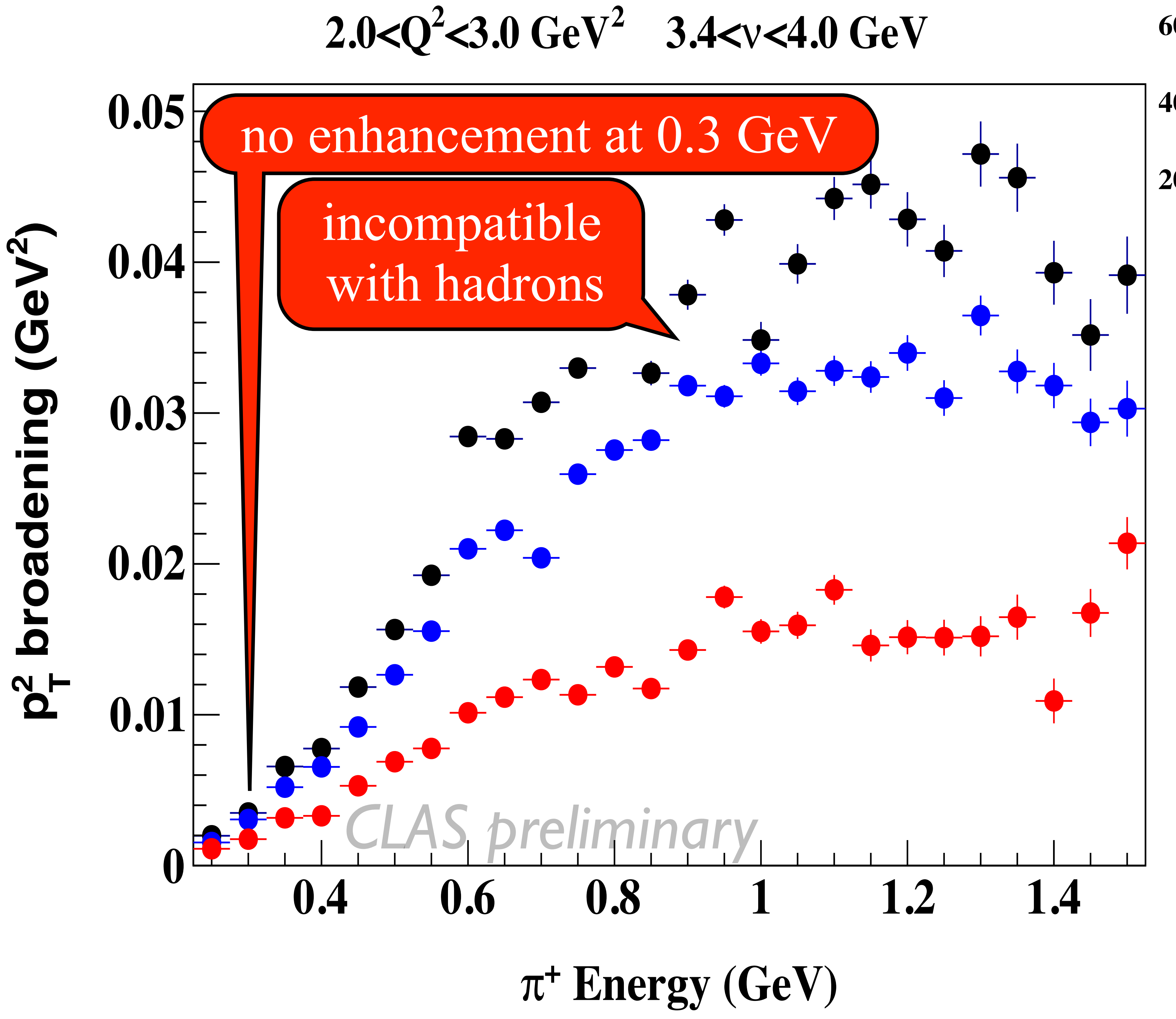

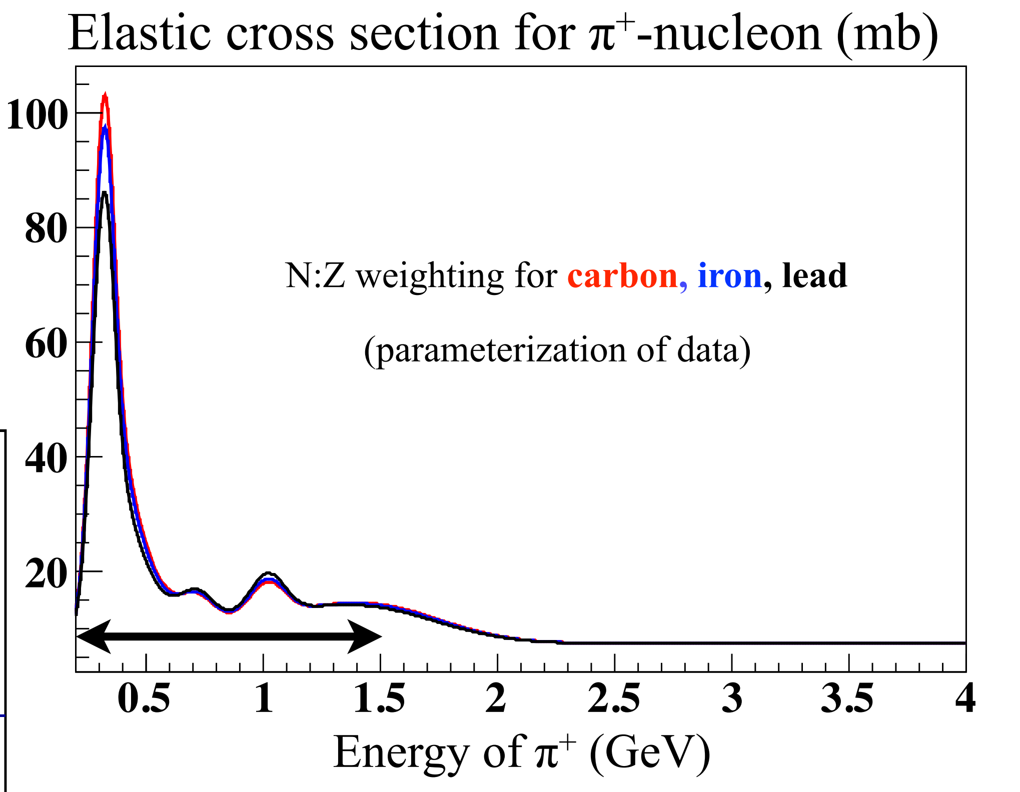

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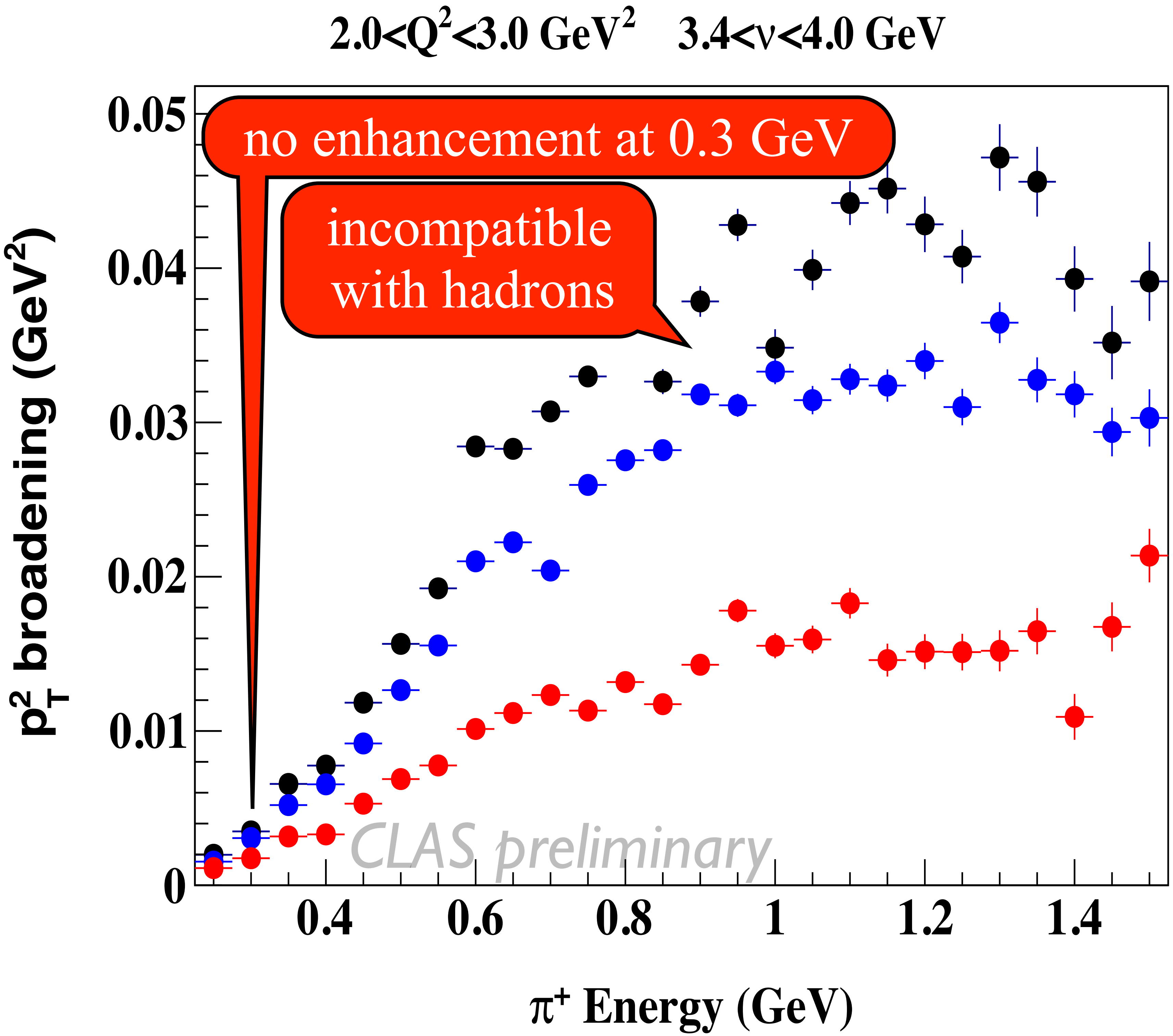
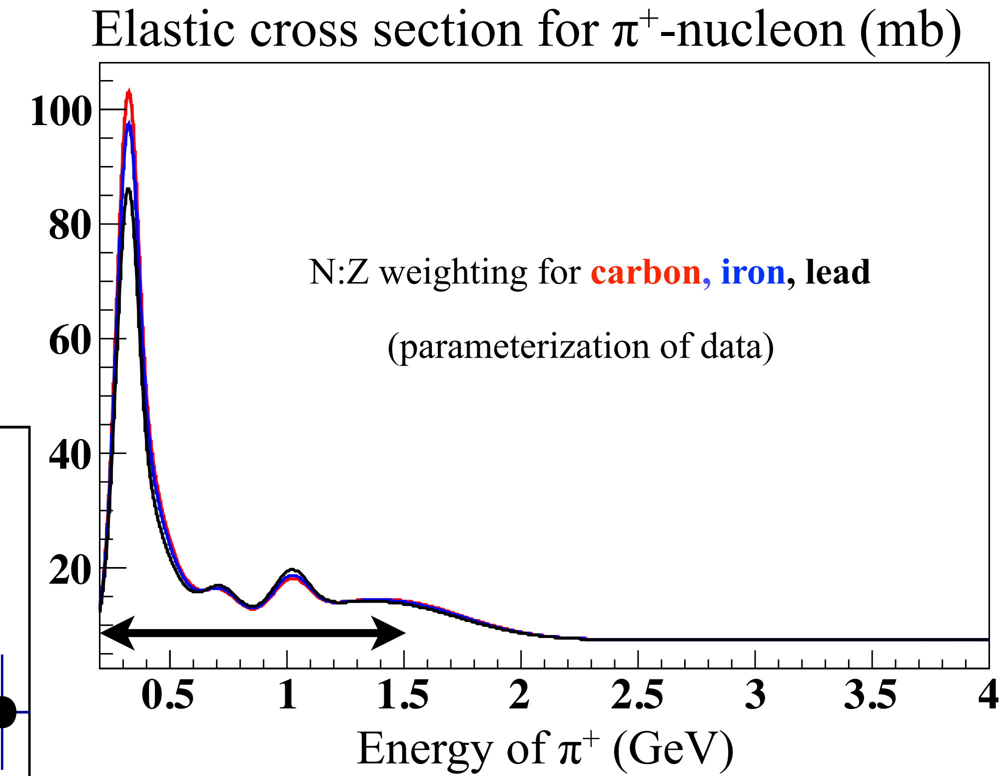
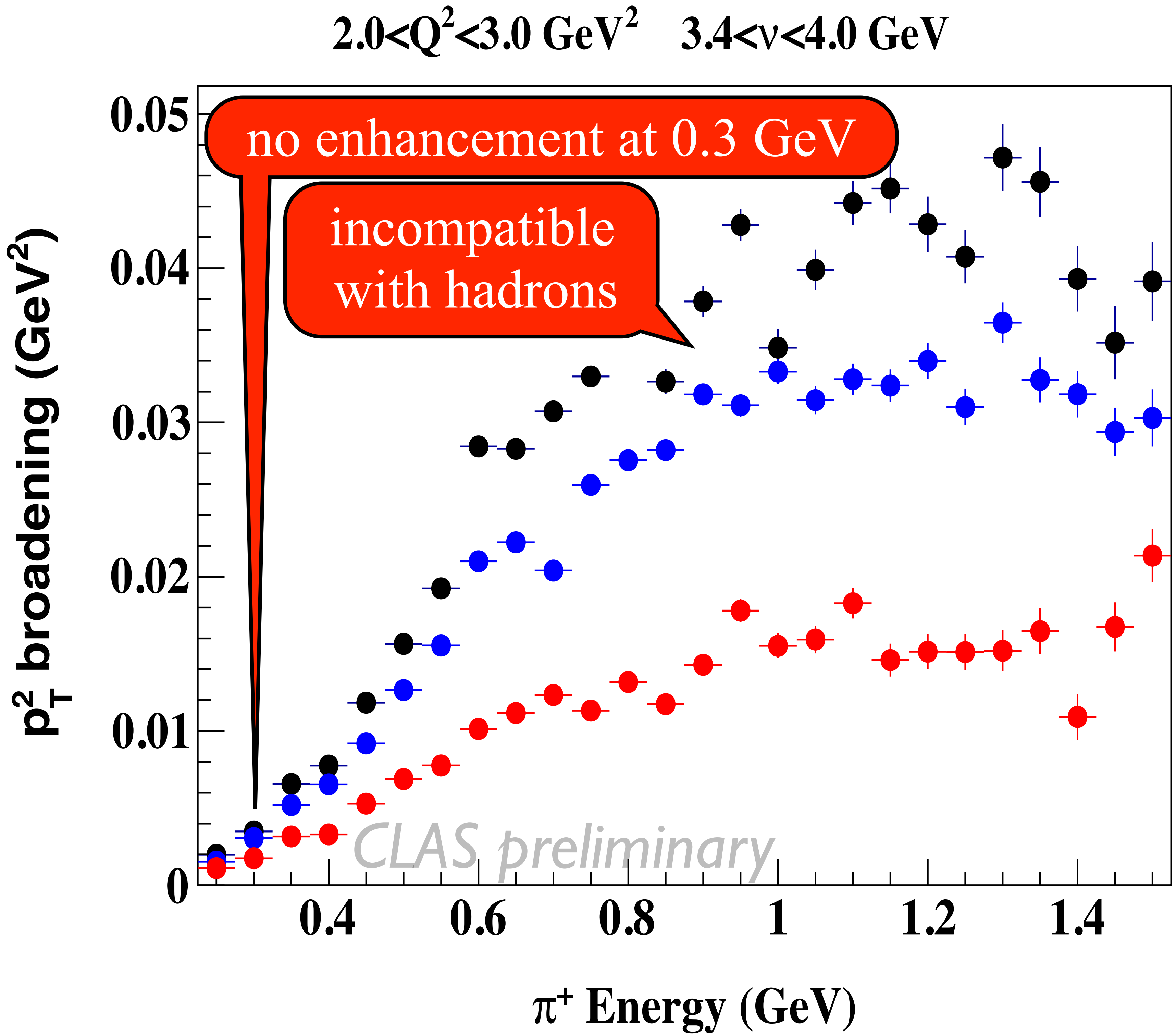
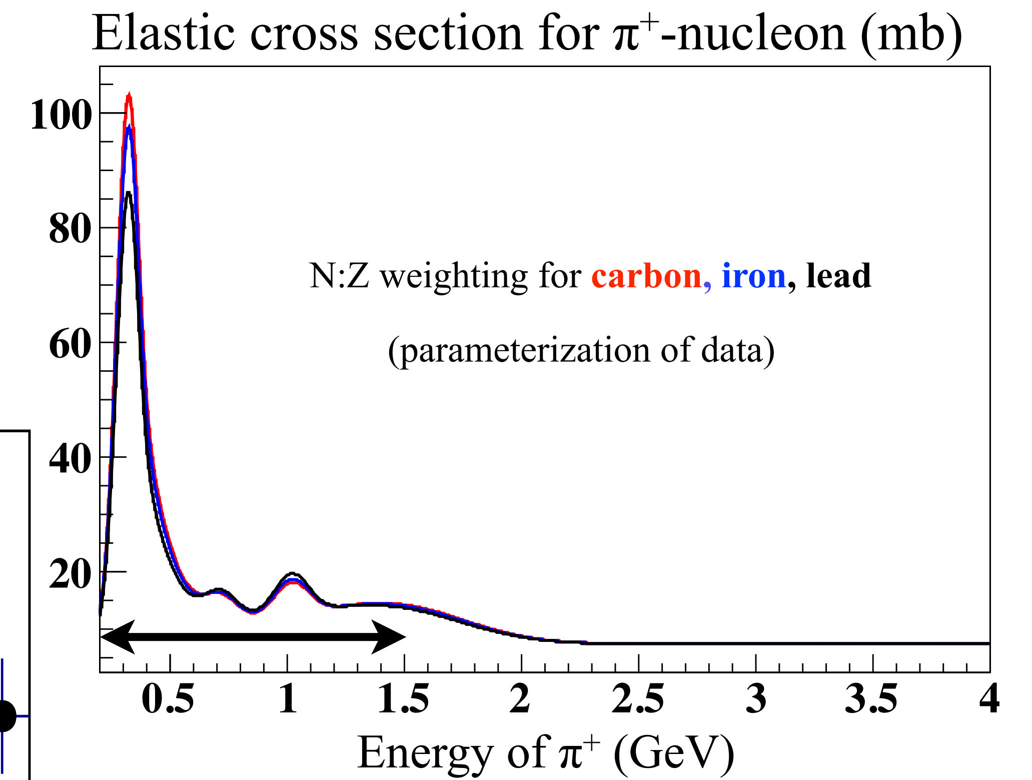




No visible evidence of hadronic elastic scattering? Suggests:

p_T^2 Broadening vs. Hadron Energy





No visible evidence of hadronic elastic scattering? Suggests:

1) formation length is very long

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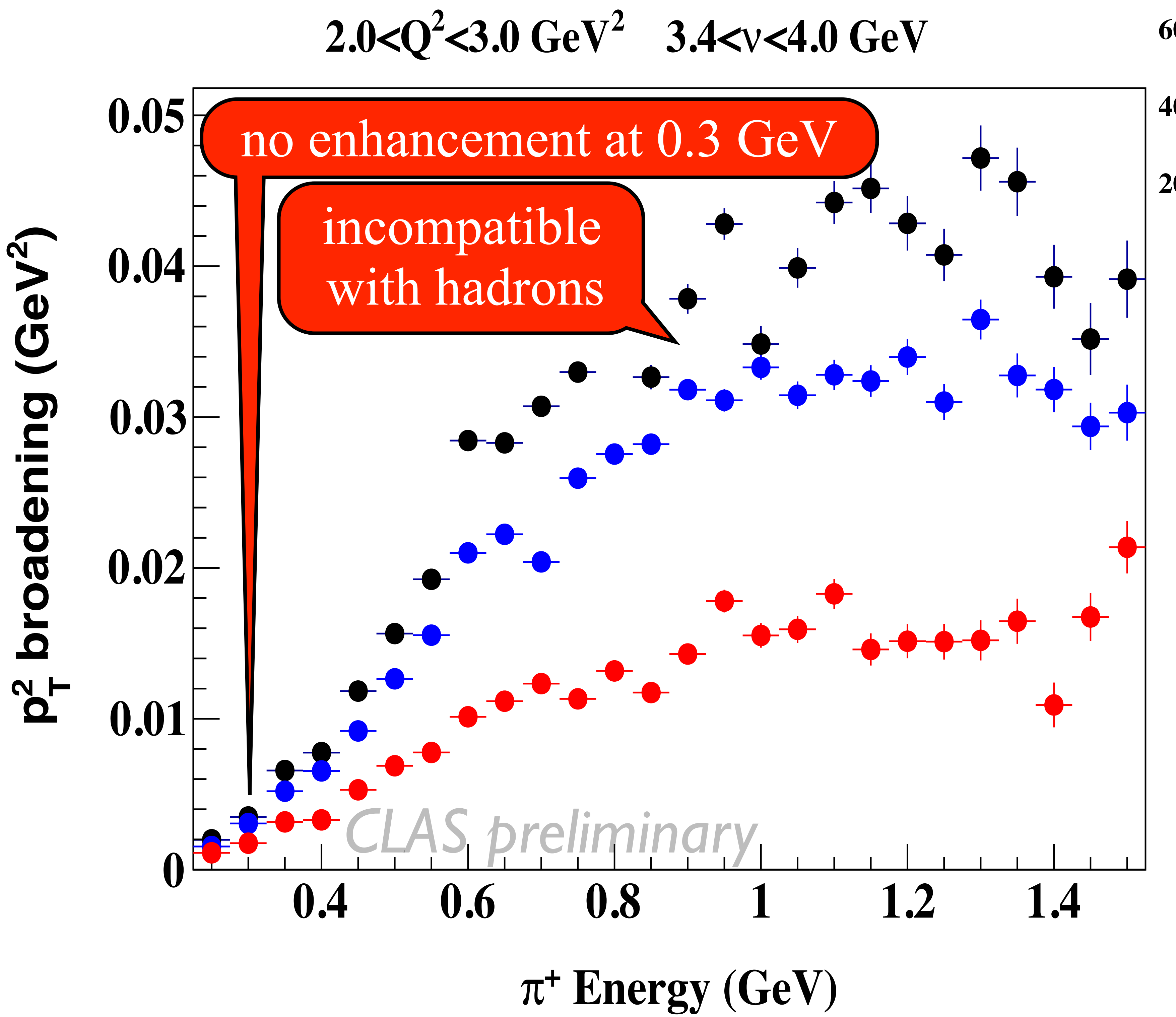

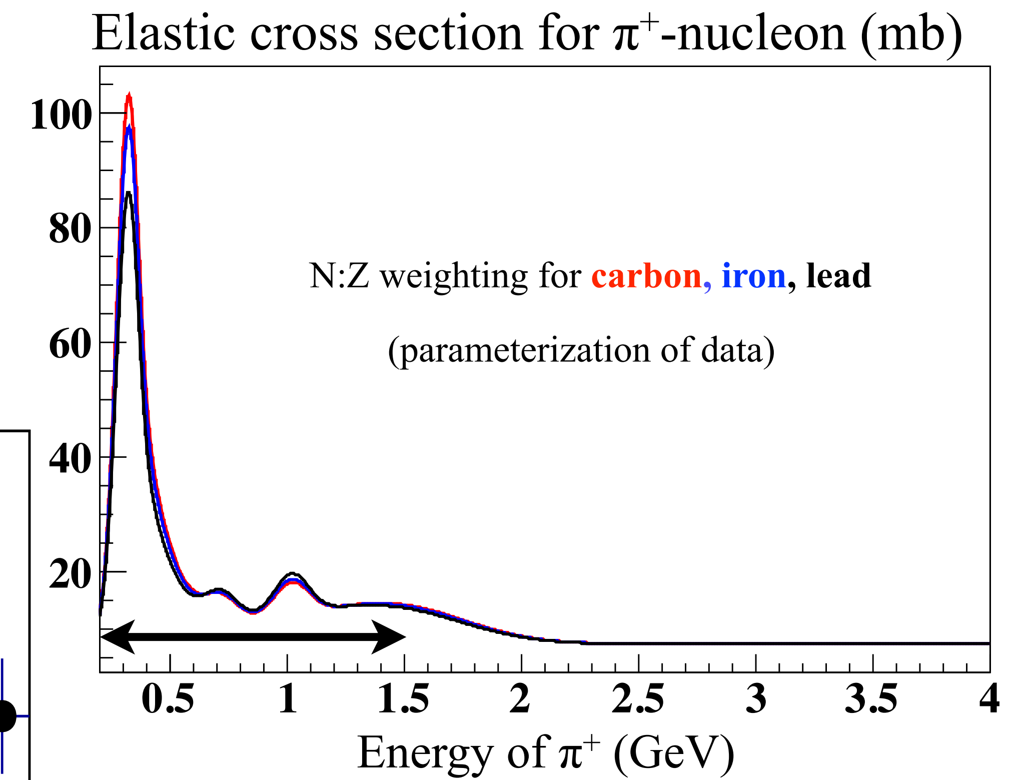

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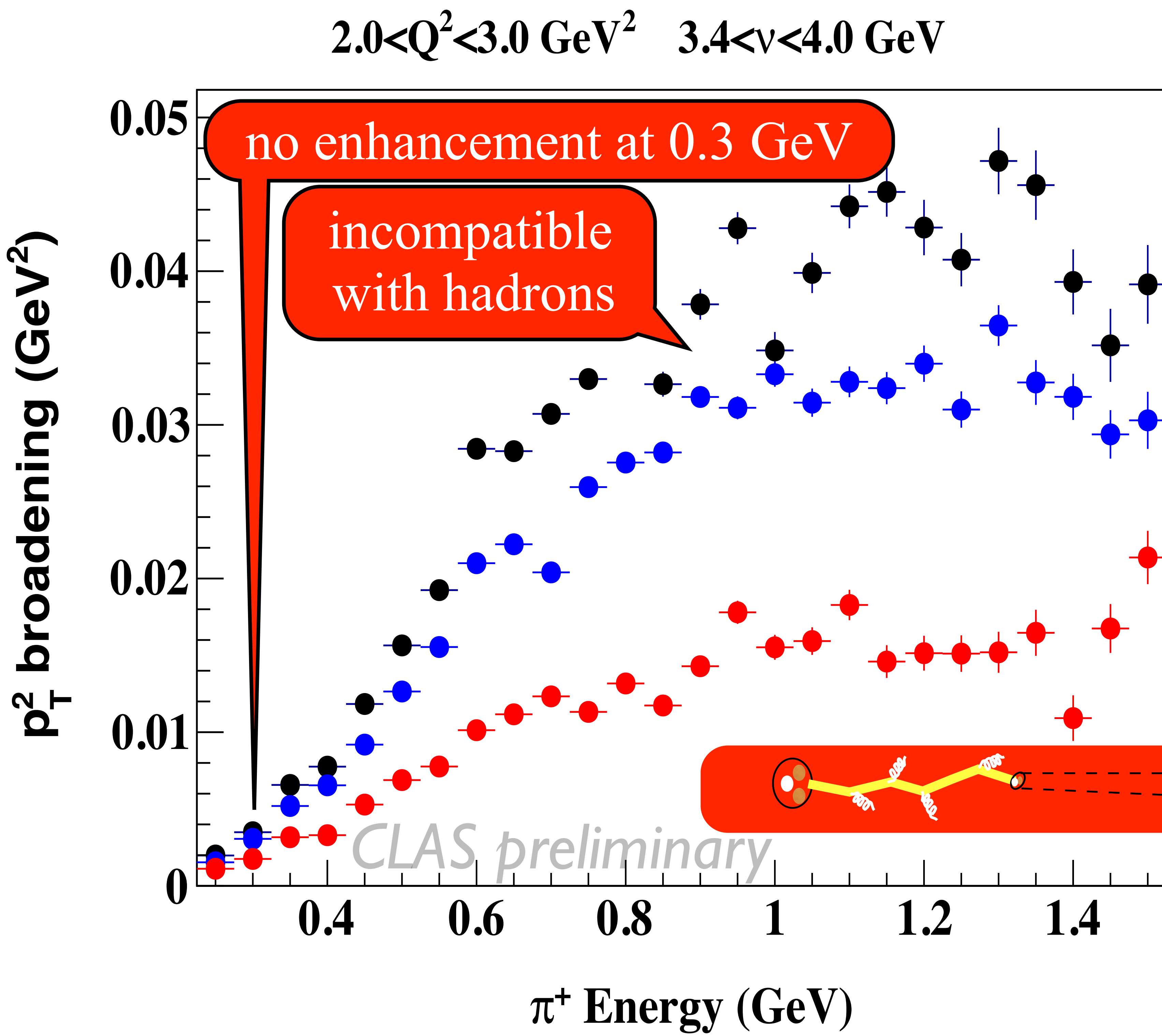

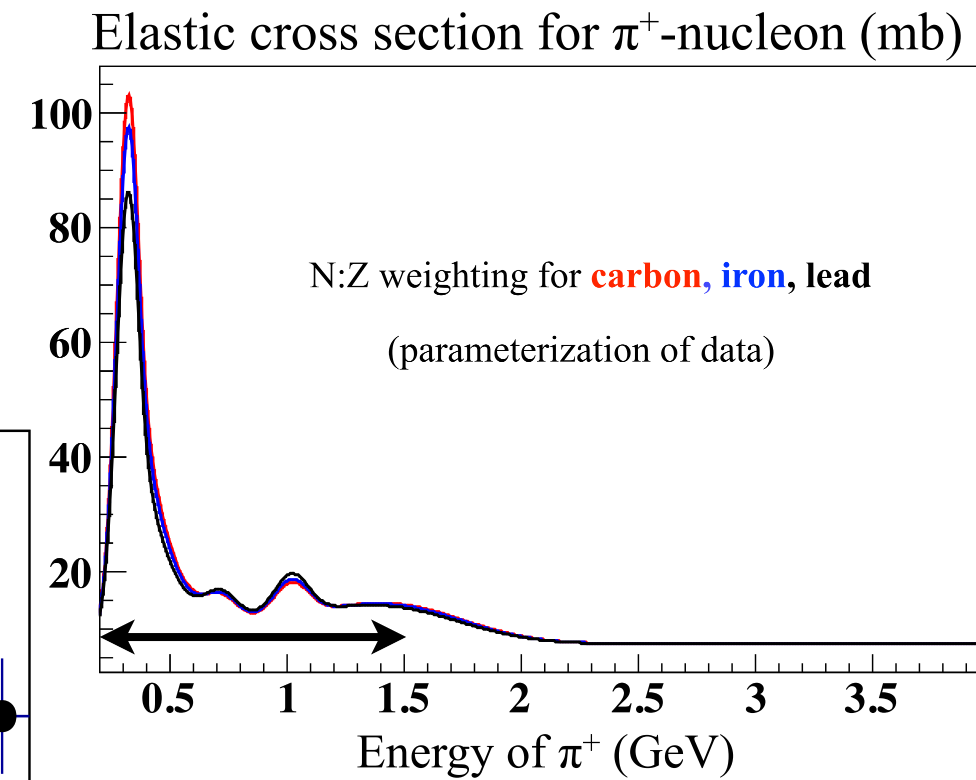

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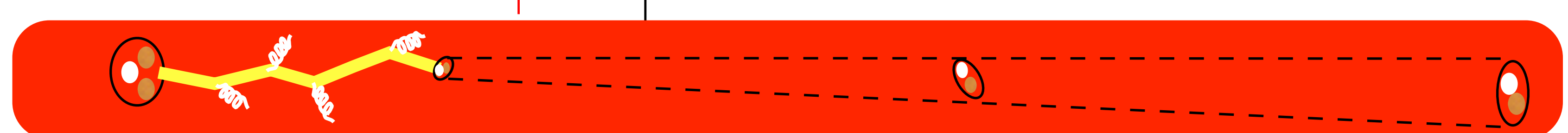

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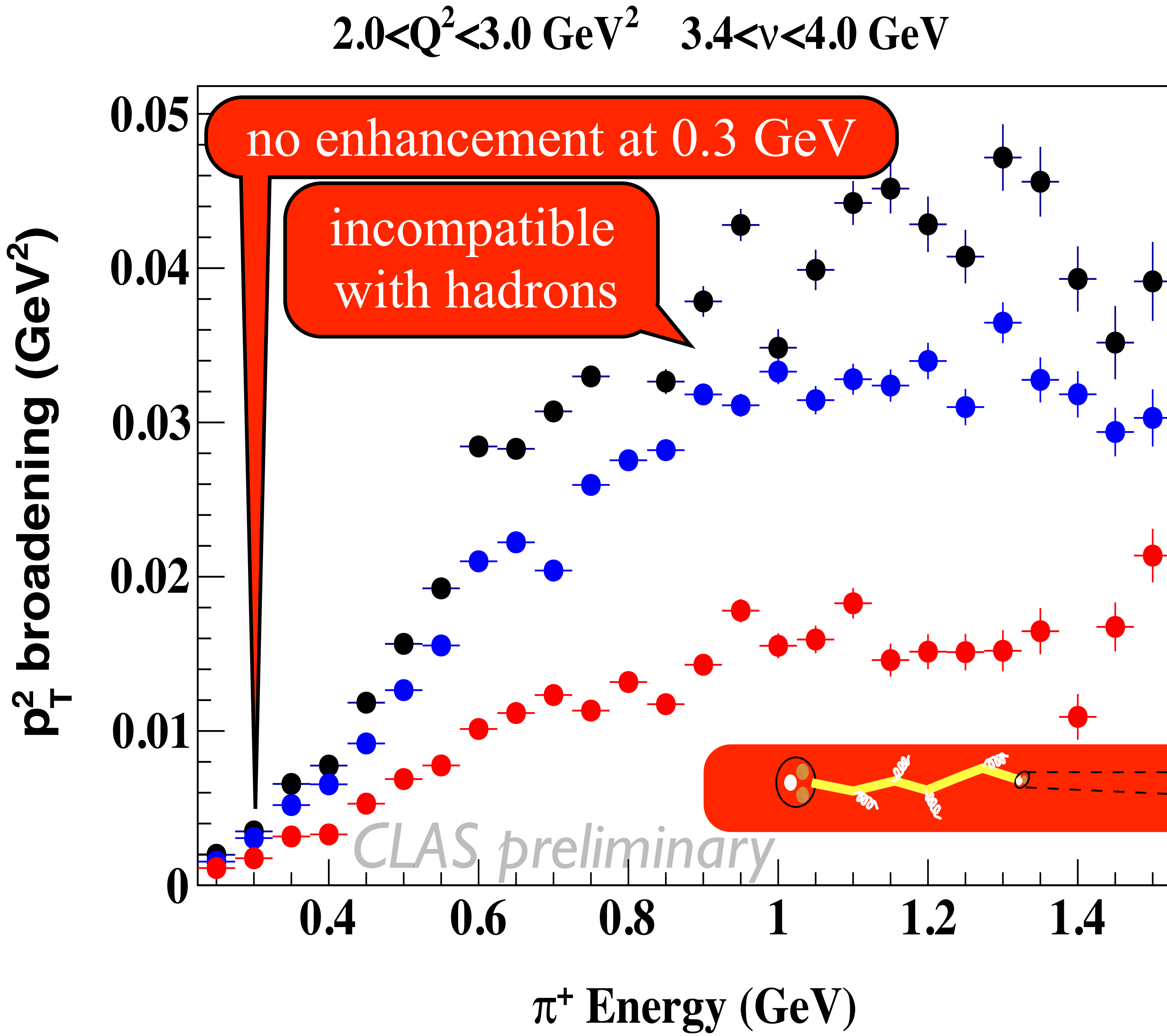
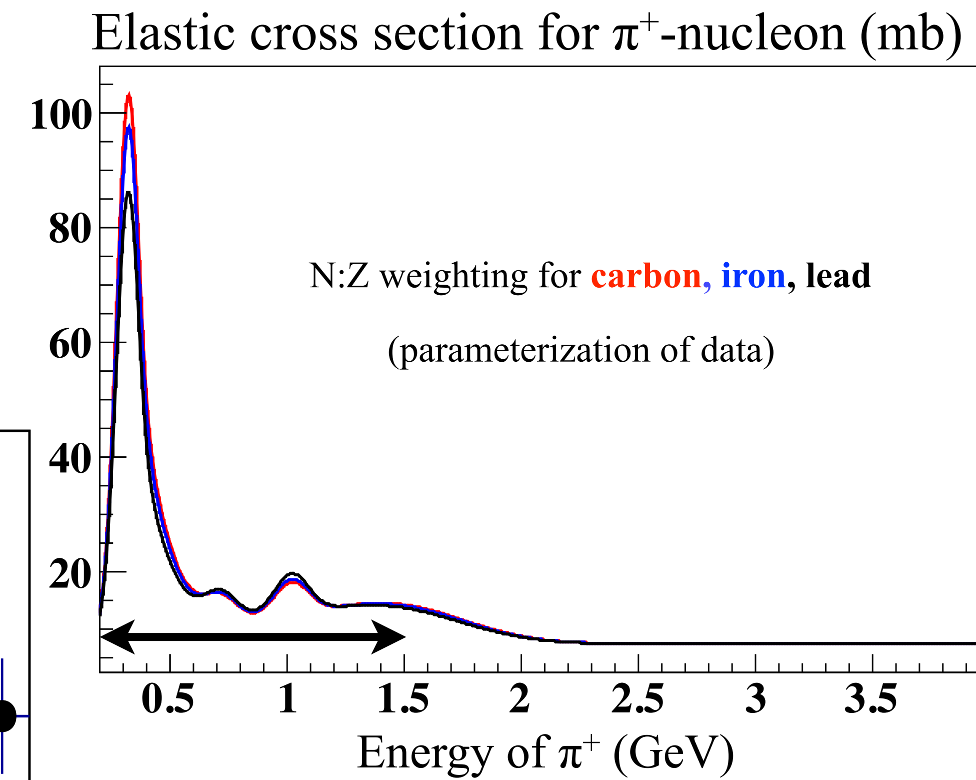
p_T^2 Broadening vs. Hadron Energy





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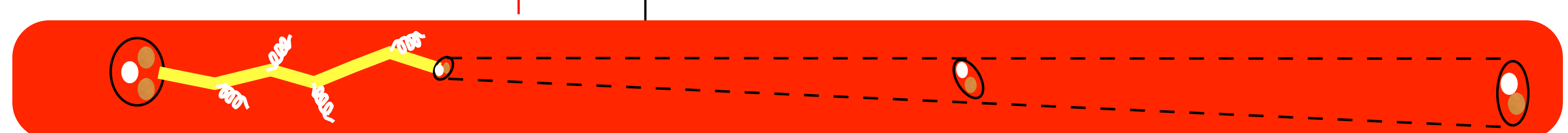
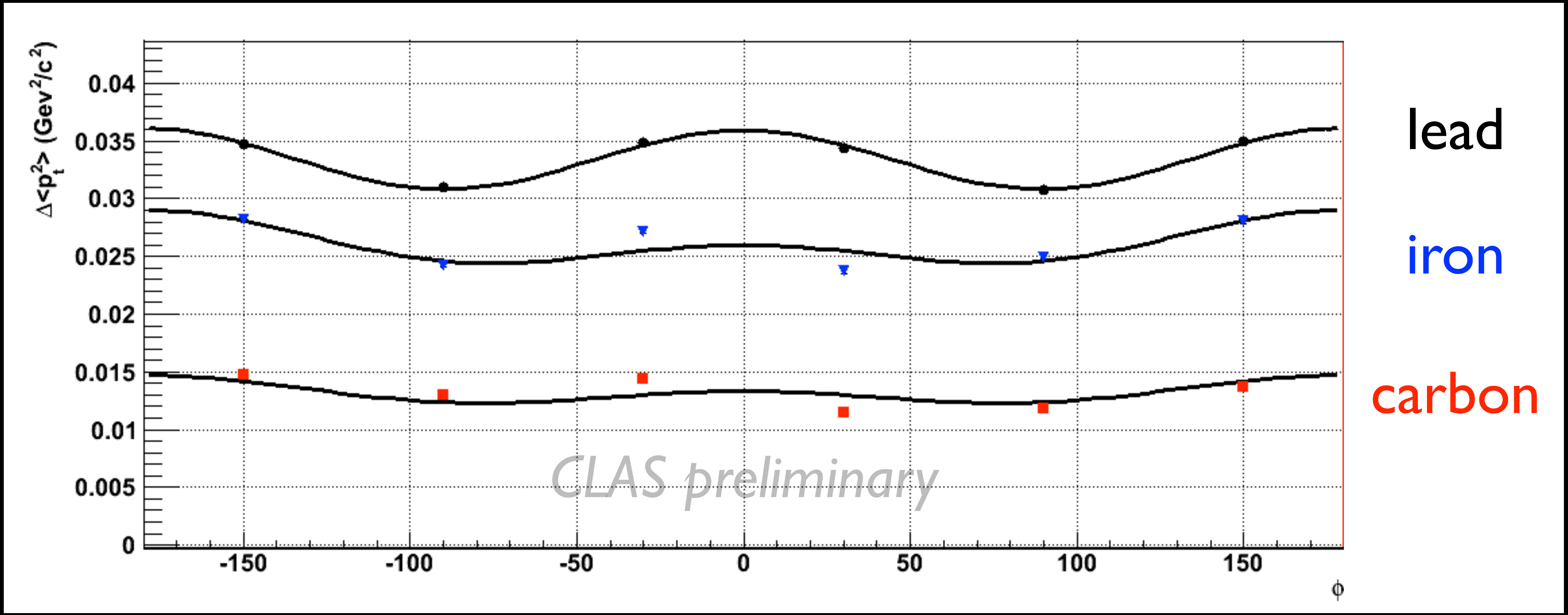


2) broadening is purely partonic

EIC: study p_T broadening of protons? Elastic cross section drops rapidly from 1 to 100 GeV/c

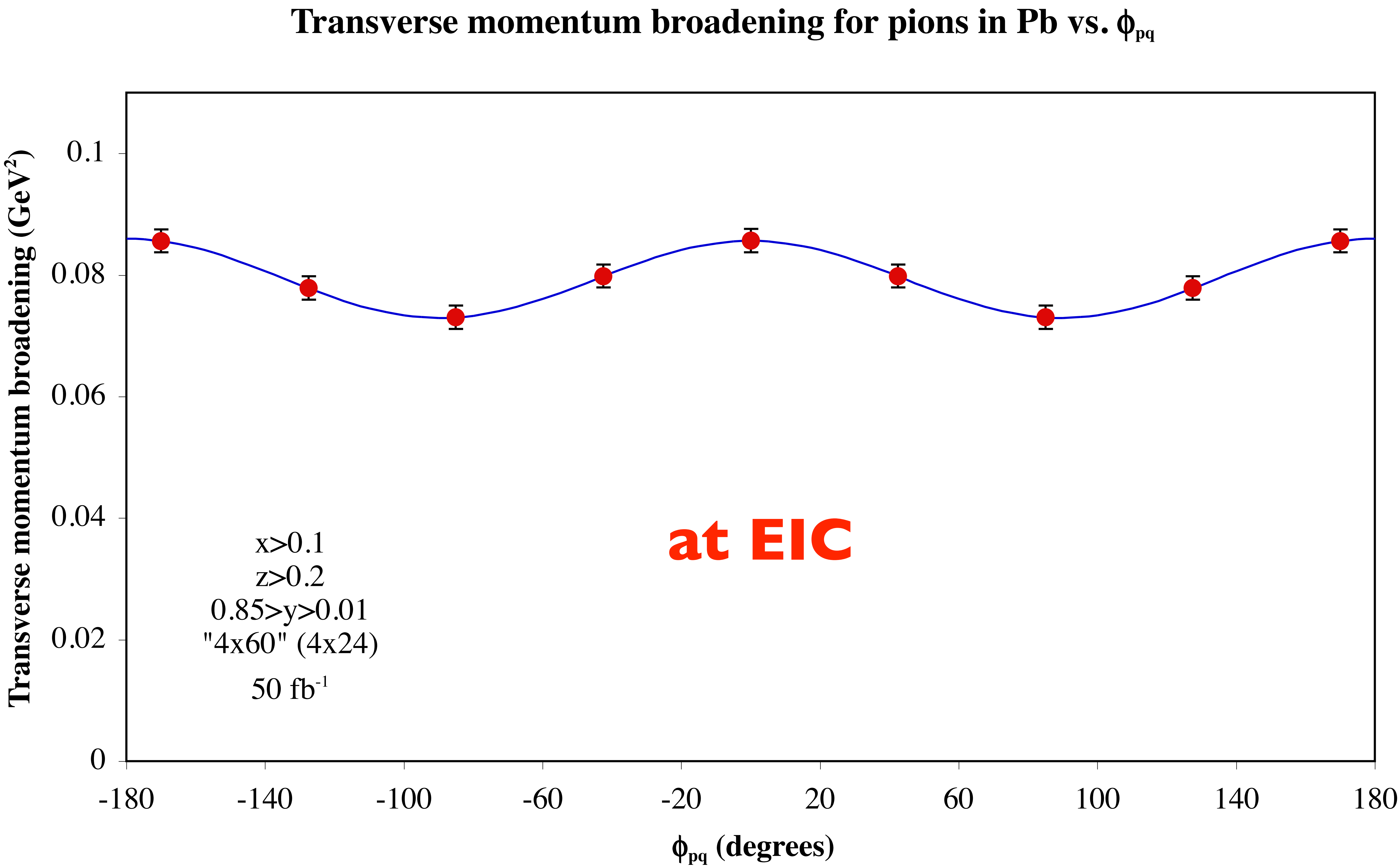
Dependence of p_T broadening on ϕ_{pq}



curves shown contain terms in $\cos(\varphi_{pq})$ and $\cos(2\varphi_{pq})$ for positive pions
only statistical uncertainties shown

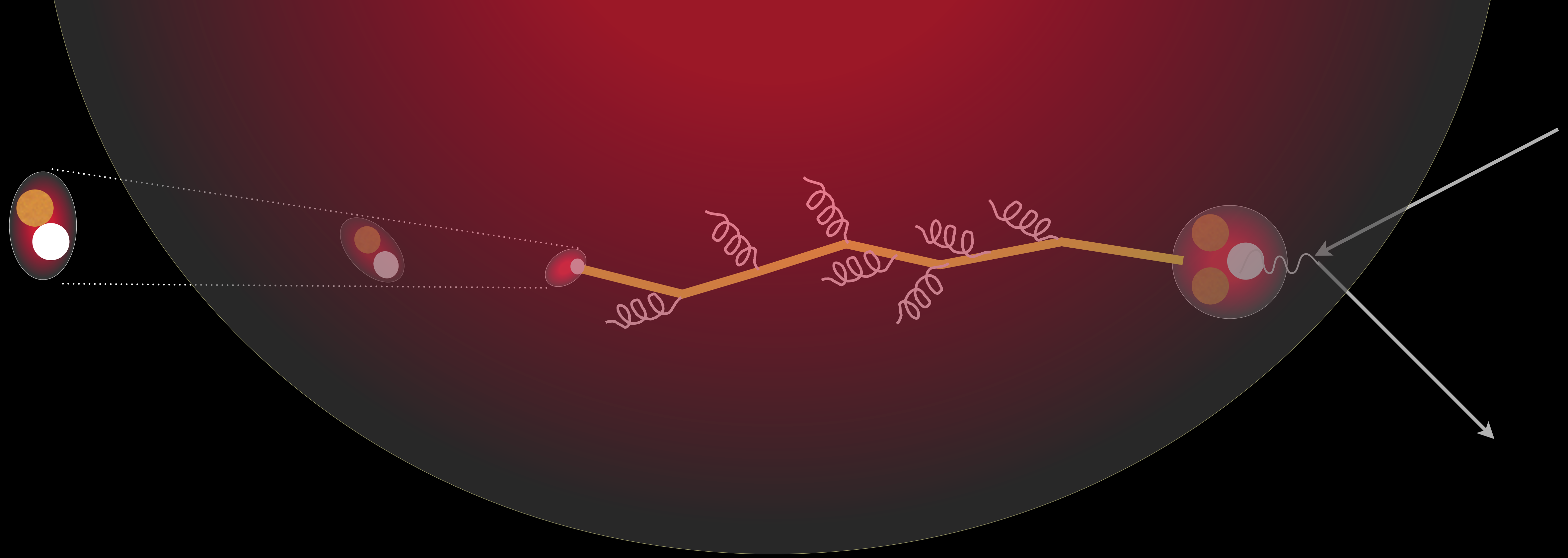
- Expectation within classical picture: any distribution seen in carbon will become more ‘washed out’ in heavier nuclei
- Not seen! *quantum effect in p_T broadening?*

  - related to parton density fluctuations in larger nuclei? J. Qiu: Boer-Mulders TMD $\otimes D_j^h(z, Q^2)$ in presence of non-vanishing mass dipole moment

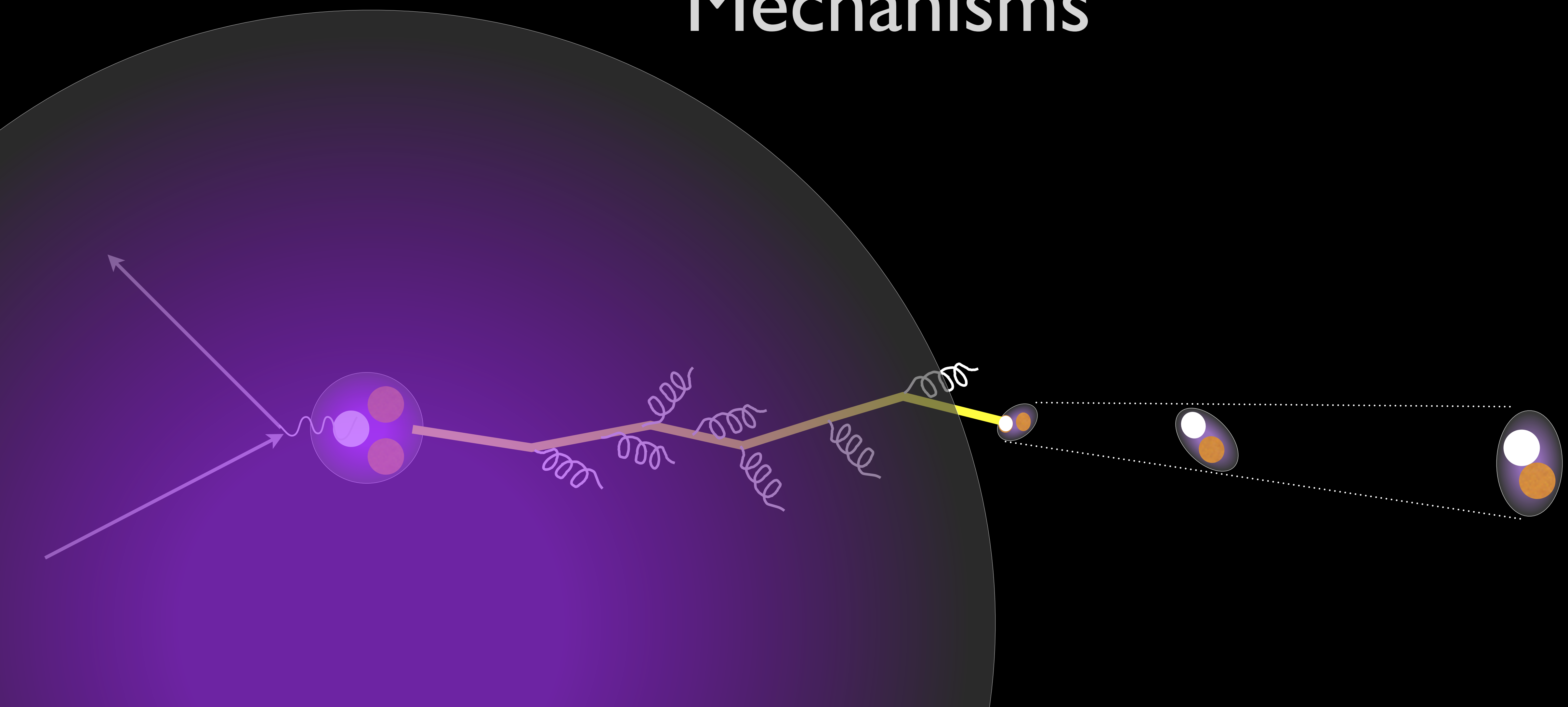


Possible p_T broadening measurement at EIC

(~speculative:) Probing quantum density fluctuations at high energies with partonic multiple scattering!



Mechanisms



Mechanisms - phenomenology

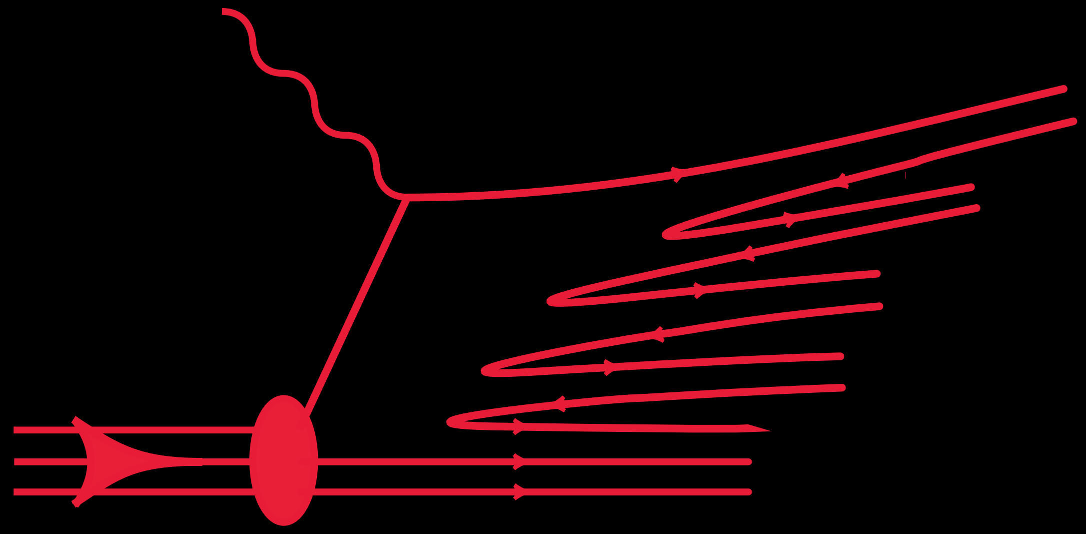
QCD cascade

NLO QCD matrix elements

Parton shower

Hadron formation

Lund string model



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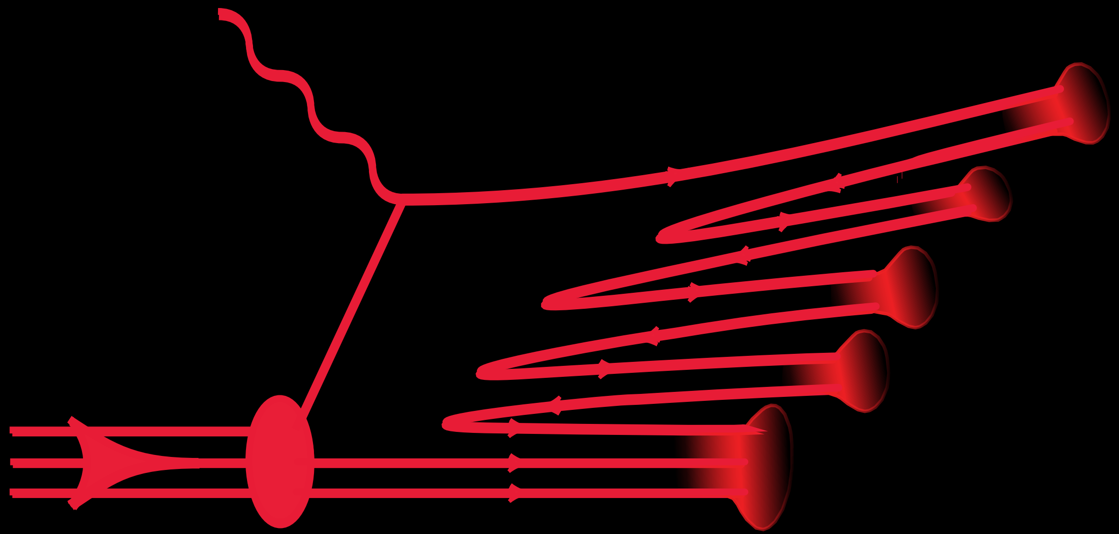
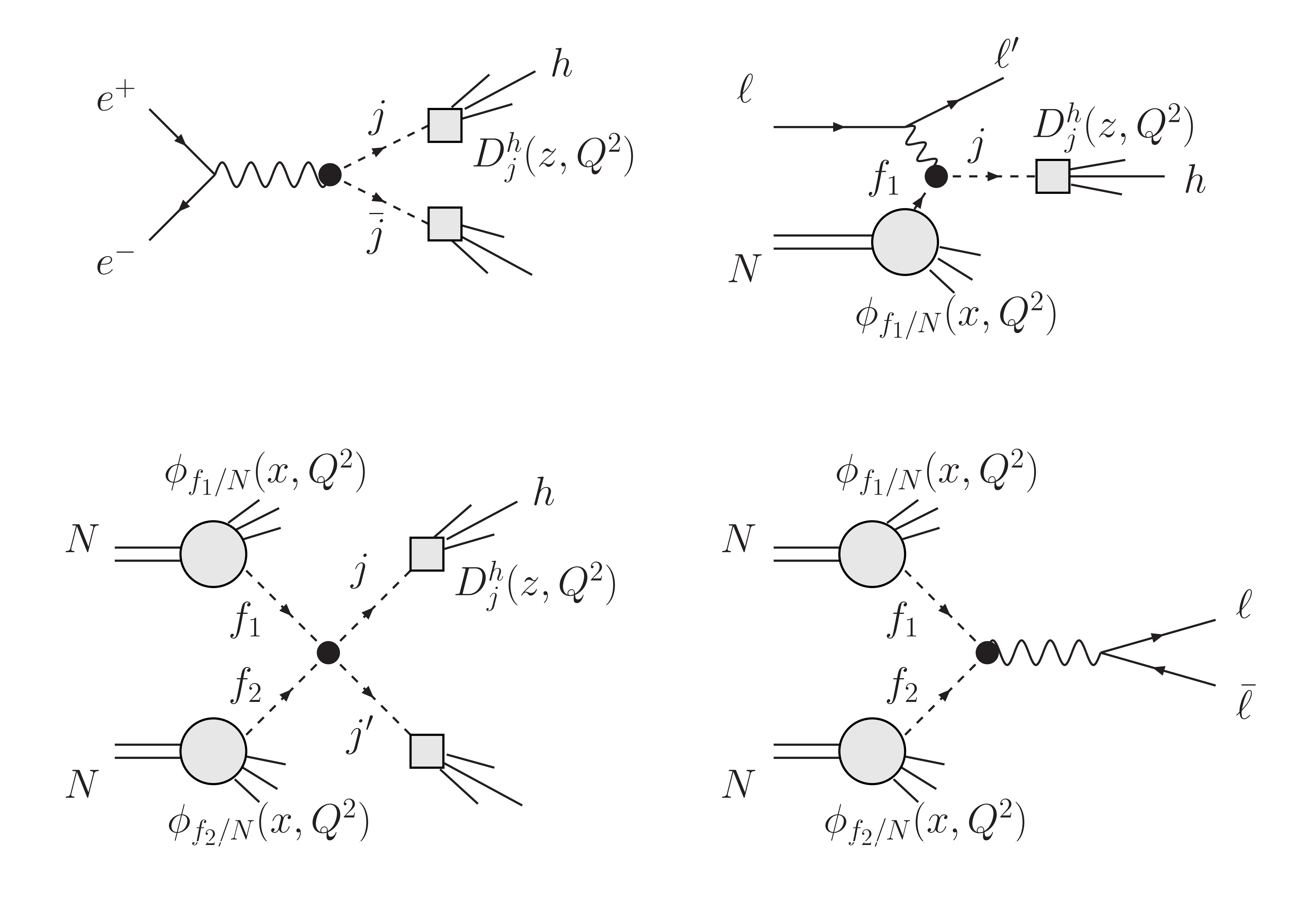


Fundamental ingredients in perturbative picture



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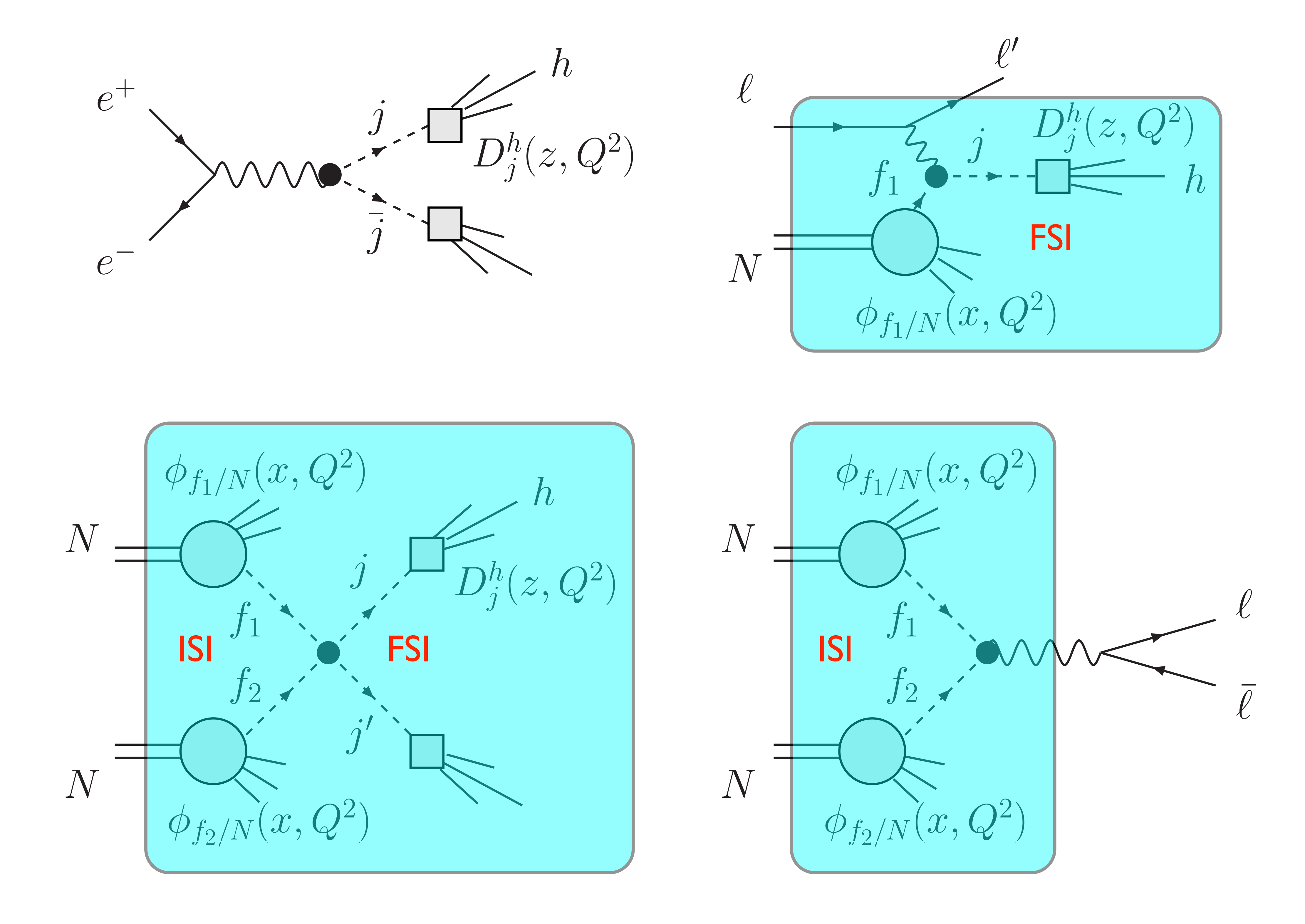


Fragmentation functions - vacuum

Fragmentation functions measured on the proton

Fragmentation functions: well-defined, universal pQCD functions describing evolution from quark to hadron

${}_{q}D^{h}(z,\mu)$ describes $q \rightarrow h$ where q=u, d, s, c, b and antiquarks

e^+e^-, SIDIS, hadron-hadron can be combined in global analysis

DGLAP equations govern their Q^2 evolution

Not calculable with lattice (no local OPE → no lattice formulation)

Estimate of errors is crucial

SIDIS: disentangle quark from anti-quark fragmentation

EIC will provide groundbreaking data for precision determinations of fragmentation functions on the proton!

Fragmentation functions - medium

- Fragmentation functions measured on nuclei

Weight function $W(z,A,Q^2)$

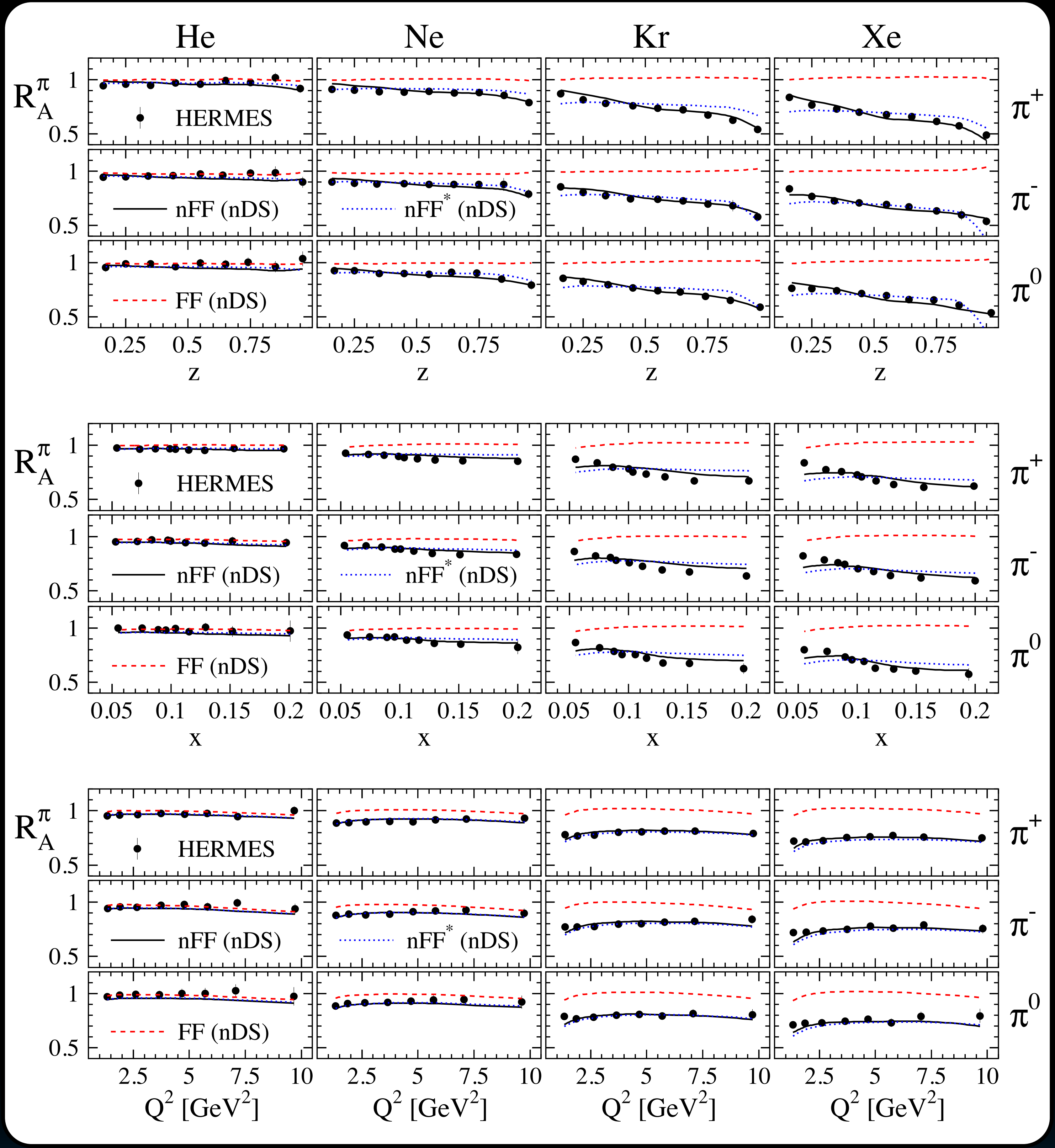
$$D^H_{i/A}(z,Q_0^2) = \int_z^1 \frac{dy}{y} W_i^H(y,A,Q_0^2)\, D_i^H(\frac{z}{y},Q_0^2)$$

One form of the weight functions:

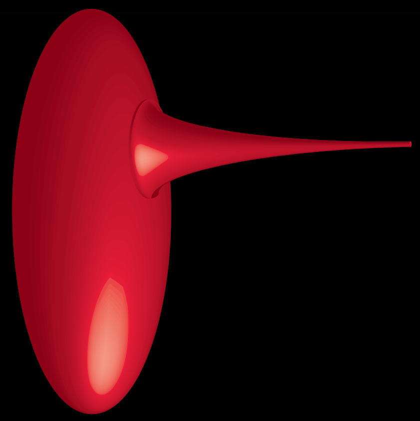
$$W_i^H(y,A,Q_0^2) = n_i\, y^{\alpha_i}(1-y)^{\beta_i}$$

Step toward a consistent pQCD framework for hard nuclear processes

Sassot, Stratmann, Zurita,
Phys. Rev. D81:054001, 2010
eA + dAu



Target Fragmentation



- The "proton with a hole" - how does it evolve?
- Target fragmentation: forward tagging at EIC

Single spin asymmetries for hadrons produced in the target fragmentation region?

Boer-Mulders Effect in production of polarized baryons in target fragmentation

Sivers, Phys. Rev. D81:034029, 2010

Sivers and Collins effects measurable in the target fragmentation region?

Can measure fracture functions (spin dependent and spin independent)?

EIC Year 1

de Florian and Sassot, Phys. Rev. D56 (1997) 426-432

Kotzinian, Anselmino, Barone, arXiv:1303.2461 [hep-ph], Phys. Lett. B699:108-118, 2011

EIC data will open up a whole new field in this area

DIS channels: *stable* hadrons, accessible with 11 GeV JLab experiment PR12-06-117

DIS channels: *stable* hadrons, accessible with 11 GeV JLab experiment PR12-06-117

meson	cτ	mass	flavor content
π^0	25 nm	0.13	$u\bar{u}d\bar{d}$
π^+, π^-	7.8 m	0.14	$u\bar{d}$, $d\bar{u}$
η	170 pm	0.55	$u\bar{u}d\bar{d}s\bar{s}$
ω	23 fm	0.78	$u\bar{u}d\bar{d}s\bar{s}$
η'	0.98 pm	0.96	$u\bar{u}d\bar{d}s\bar{s}$
ϕ	44 fm	1.0	$u\bar{u}d\bar{d}s\bar{s}$
f1	8 fm	1.3	$u\bar{u}d\bar{d}s\bar{s}$
K^0	27 mm	0.50	$d\bar{s}$
K^+, K^-	3.7 m	0.49	$u\bar{s}$, $\bar{u}s$

DIS channels: *stable* hadrons, accessible with 11 GeV JLab experiment PR12-06-117

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π^+, π^-	7.8 m	0.14	$u\bar{d}$, $d\bar{u}$
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ω	23 fm	0.78	$u\bar{u}d\bar{d}s\bar{s}$
η'	0.98 pm	0.96	$u\bar{u}d\bar{d}s\bar{s}$
ϕ	44 fm	1.0	$u\bar{u}d\bar{d}s\bar{s}$
f1	8 fm	1.3	$u\bar{u}d\bar{d}s\bar{s}$
K^0	27 mm	0.50	$d\bar{s}$
K^+, K^-	3.7 m	0.49	$u\bar{s}$, $\bar{u}s$

baryon	cτ	mass	flavor content
p	stable	0.94	ud
$\bar{p}$	stable	0.94	$\overline{ud}$
Λ	79 mm	1.1	uds
$\Lambda(1520)$	13 fm	1.5	uds
Σ^+	24 mm	1.2	us
Σ^-	44 mm	1.2	ds
Σ^0	22 pm	1.2	uds
Ξ^0	87 mm	1.3	us
Ξ^-	49 mm	1.3	ds

DIS channels: *stable* hadrons, accessible with 11 GeV JLab experiment PR12-06-117

Actively underway with existing 5 GeV data

meson	cτ	mass	flavor content
π^0	25 nm	0.13	$u\bar{u}d\bar{d}$
π^+, π^-	7.8 m	0.14	$u\bar{d}$, $d\bar{u}$
η	170 pm	0.55	$u\bar{u}d\bar{d}s\bar{s}$
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DIS channels: *stable* hadrons, accessible with 11 GeV JLab experiment PR12-06-117

Actively underway with existing 5 GeV data

EIC: heavy mesons and baryons; wide kinematic range!

meson	cτ	mass	flavor content
π^0	25 nm	0.13	uudd
π^+, π^-	7.8 m	0.14	ud, du
η	170 pm	0.55	uuddss
ω	23 fm	0.78	uuddss
η'	0.98 pm	0.96	uuddss
ϕ	44 fm	1.0	uuddss
$f1$	8 fm	1.3	uuddss
K^0	27 mm	0.50	ds
K^+, K^-	3.7 m	0.49	us, us

baryon	cτ	mass	flavor content
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Conclusions

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- Color propagation, neutralization, and fluctuations are fascinating and mysterious topics

Impossible classically, counter-intuitive, yet ubiquitous in hard processes

and a fundamental part of QCD

Conclusions

- **Color propagation, neutralization, and fluctuations are fascinating and mysterious topics**

Impossible classically, counter-intuitive, yet ubiquitous in hard processes

and a fundamental part of QCD

- **EIC: enormous opportunities for important advances**

Year-1 results: potential for dramatic breakthroughs in our understanding of QCD

Direct tests of string model time dependence

The puzzle of heavy quark energy loss

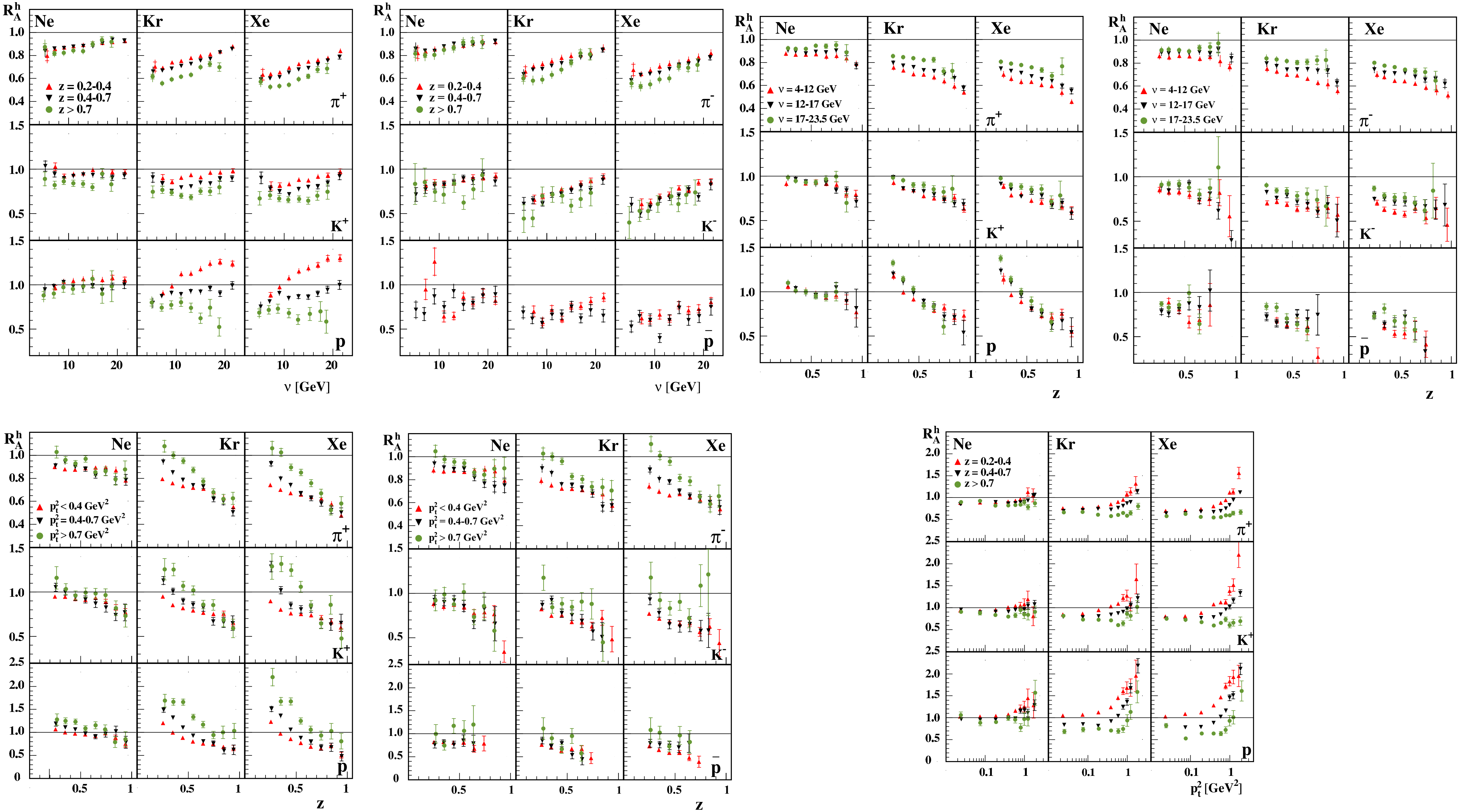
Transformational expansion of our understanding: target fragmentation

Gluonic fluctuations and hadronization mechanisms, 2^{nd} generation experiments

Wide kinematic reach of EIC is crucial

Exploring QCD in cold nuclear matter using colored partonic probes!

Additional Slides

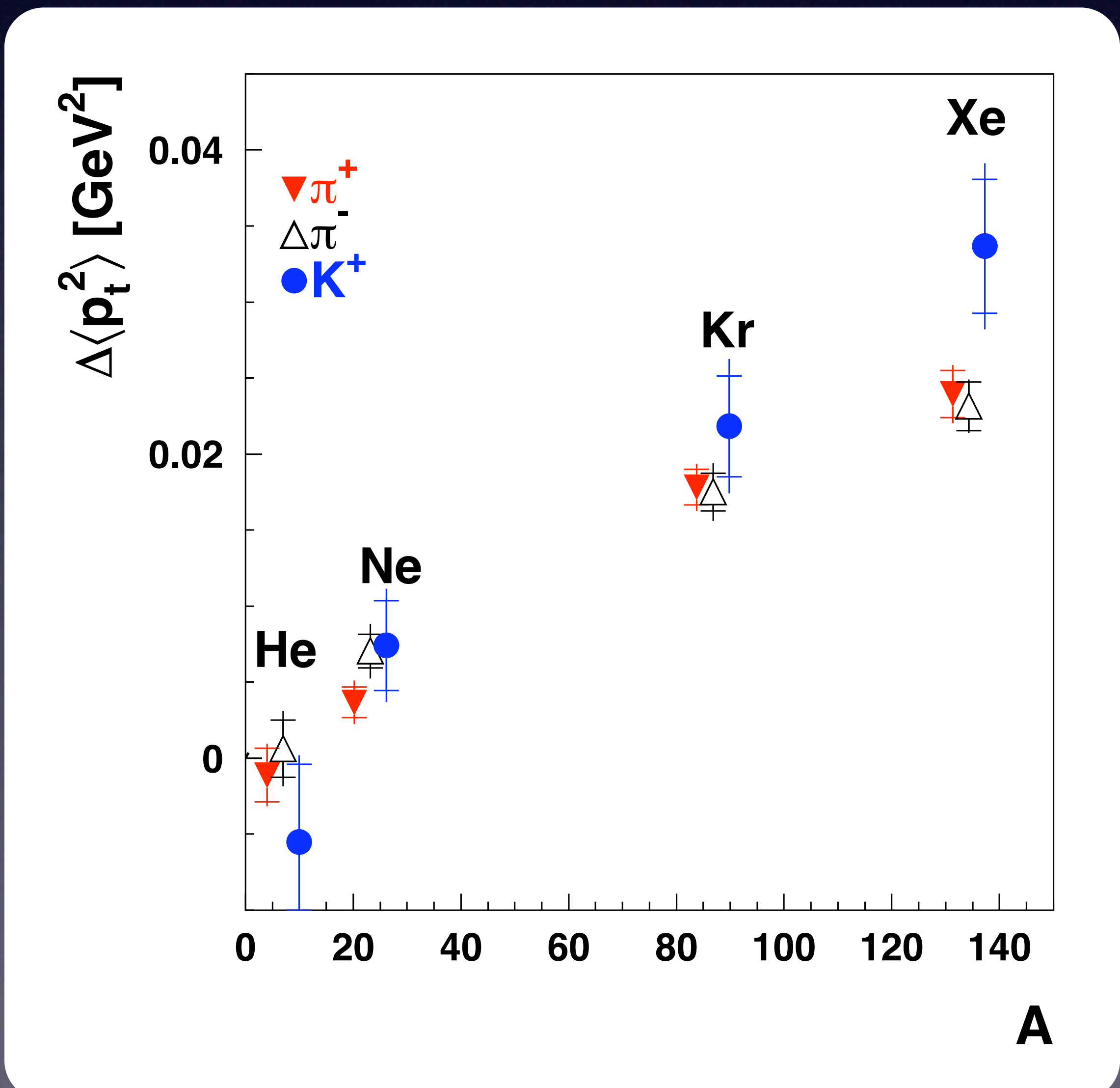


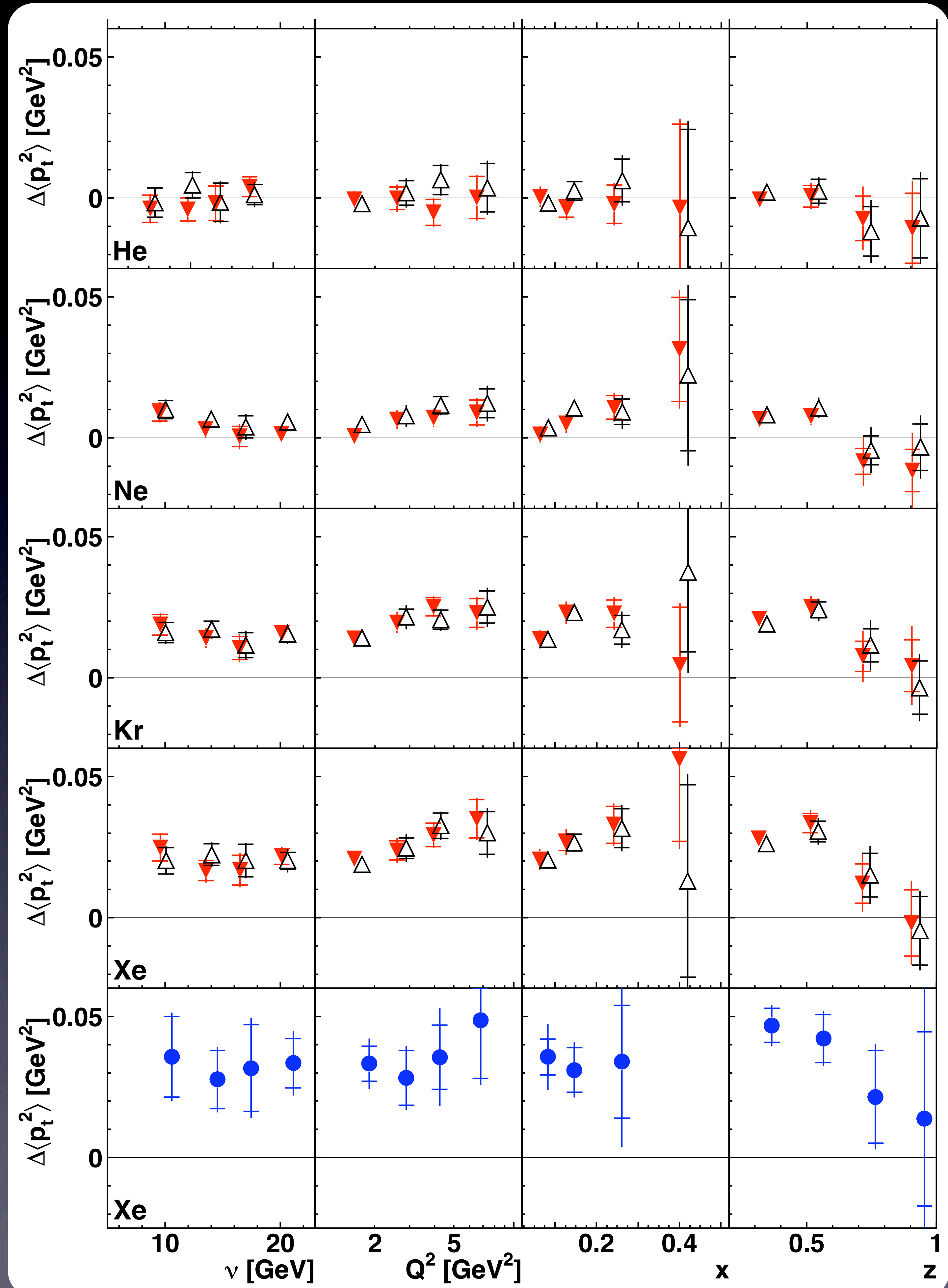
Hermes 2-D studies of multiplicity ratios for π,K,p

Eur. Phys. J. A (2011) 47: 113

Hermes p_T broadening data

World's first comparison between pion and K^+ p_T broadening



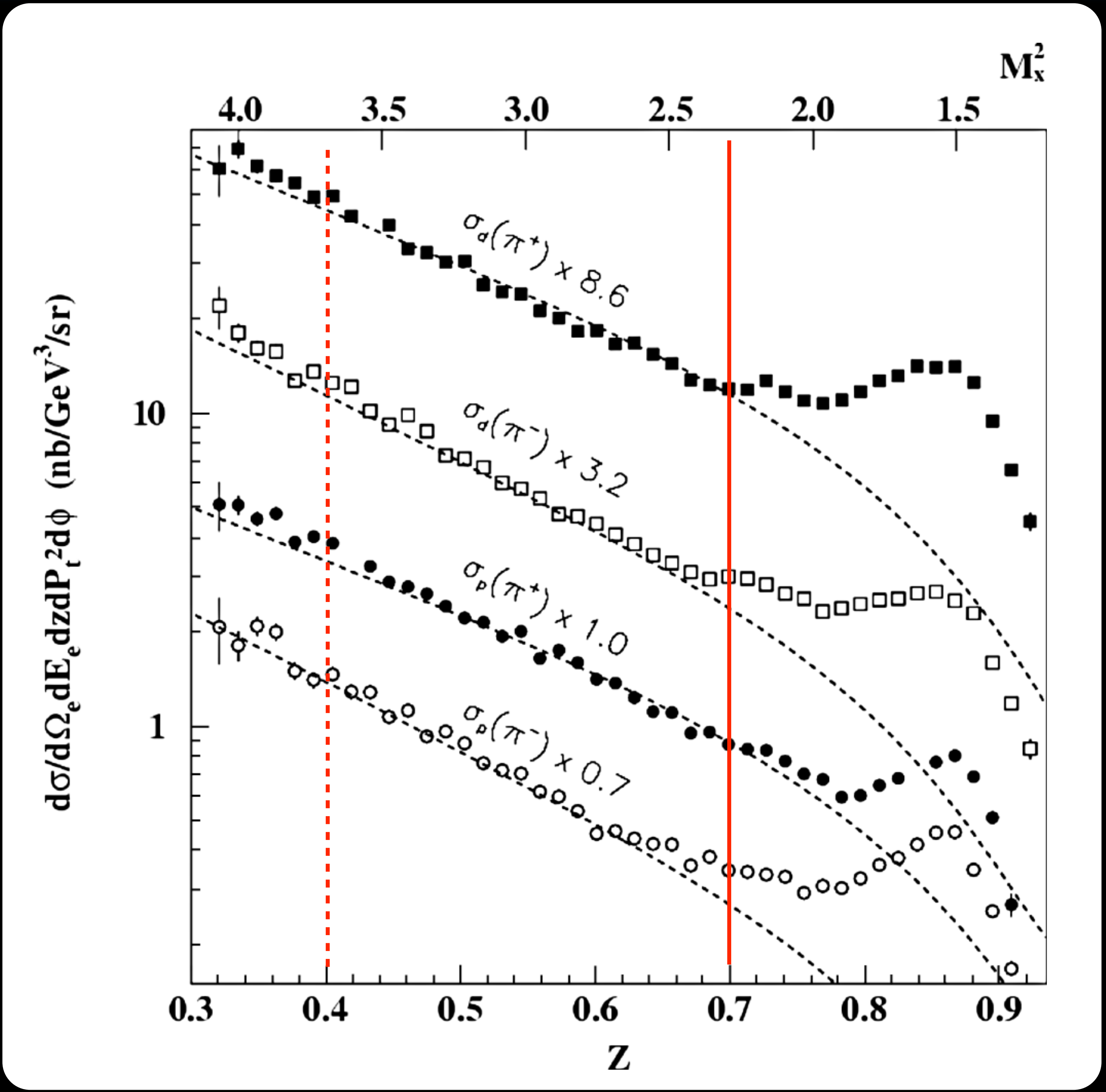


Factorization and interpretability

Hall C data

Precocious factorization

Limited deviation

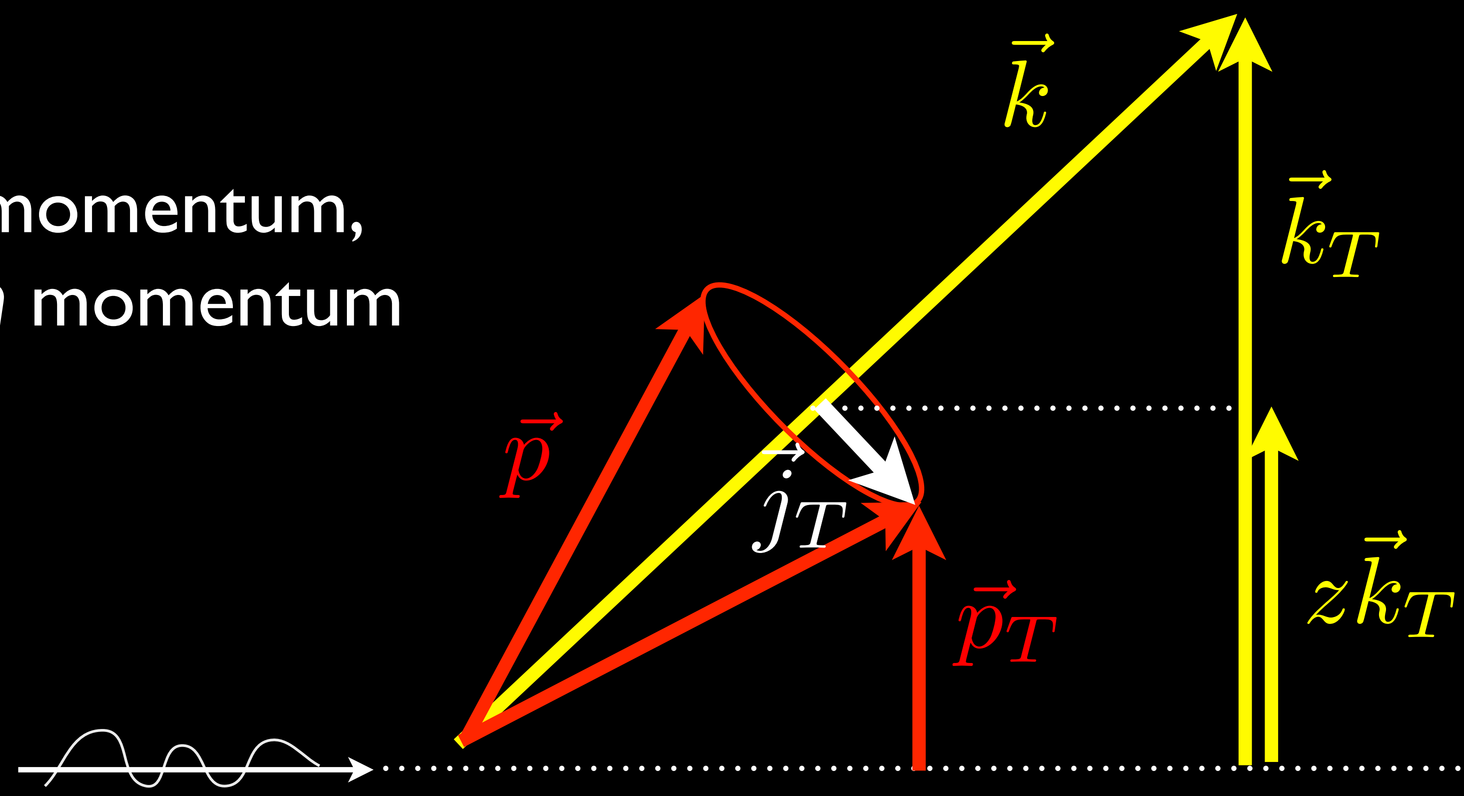


T. Navasardyan, et al., PRL 98, 022001 (2007)

Quark k_T broadening vs. *hadron* p_T broadening

The k_T broadening experienced by a quark is "*diluted*" in the fragmention process

k is the ***quark*** momentum,
p is the ***hadron*** momentum



$$\vec{p}_T = z\vec{k}_T + \vec{j}_T$$

$$\langle p_T^2 \rangle = \langle z^2 k_T^2 \rangle + \langle j_T^2 \rangle$$

$$\Delta\langle p_T^2 \rangle = \Delta\langle z^2 k_T^2 \rangle + \cancel{\Delta\langle j_T^2 \rangle} \sim 0$$

$$\boxed{\Delta\langle p_T^2 \rangle \approx z^2 \Delta\langle k_T^2 \rangle}$$

Verified for pions to 5-10% accuracy for vacuum case, z=0.4-0.7, by Monte Carlo studies

Basic questions at low energies:

Partonic processes dominate, or hadronic? in which kinematic regime? classical or quantum?

Can identify dominant hadronization mechanisms, uniquely? what are the roles of flavor and mass?

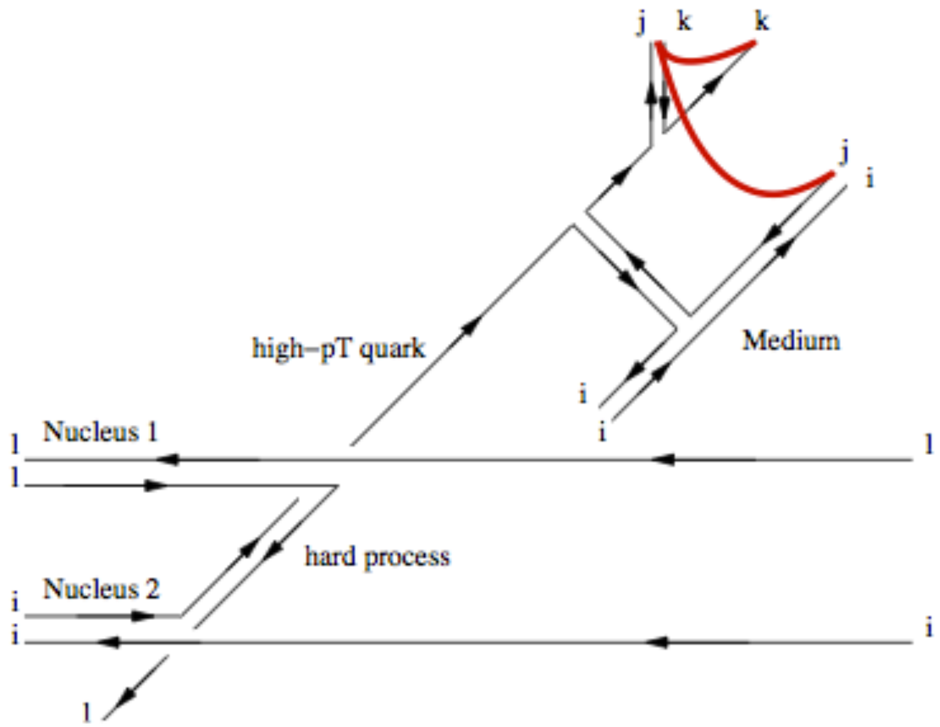
What can we infer about fundamental QCD processes by observing the interaction with the nucleus?

If p_T broadening uniquely signals the partonic stage, can use this as one tool to answer these questions

Color correlations versus kinematics

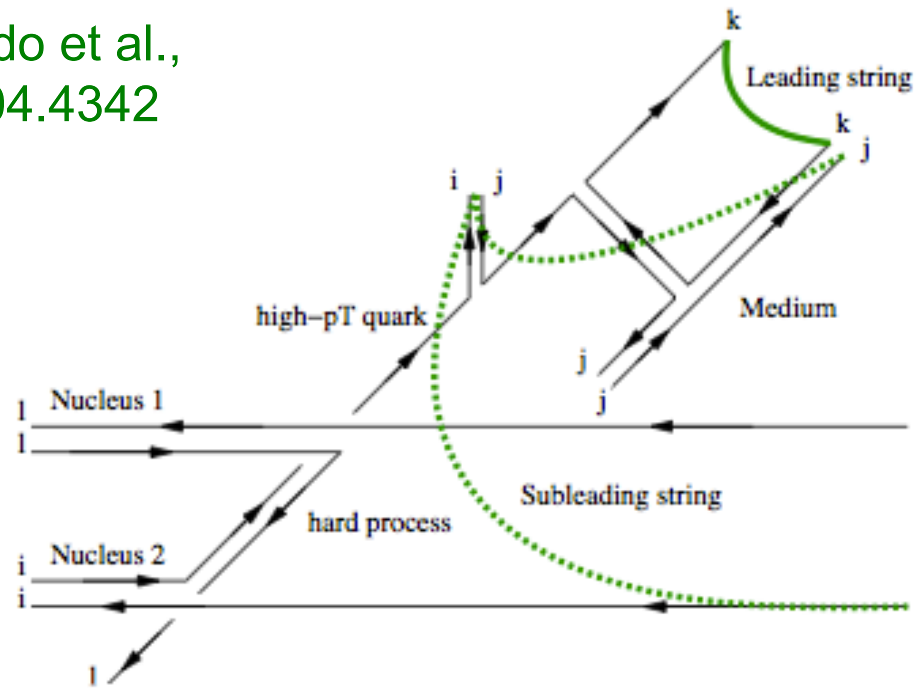
Even if hadron forms outside medium, it may form from modified color connection

- Vacuum-like hadronization
  (q & g contribute to leading hadron)



- Medium-modified hadronization
  (glue cannot contribute to leading hadron)

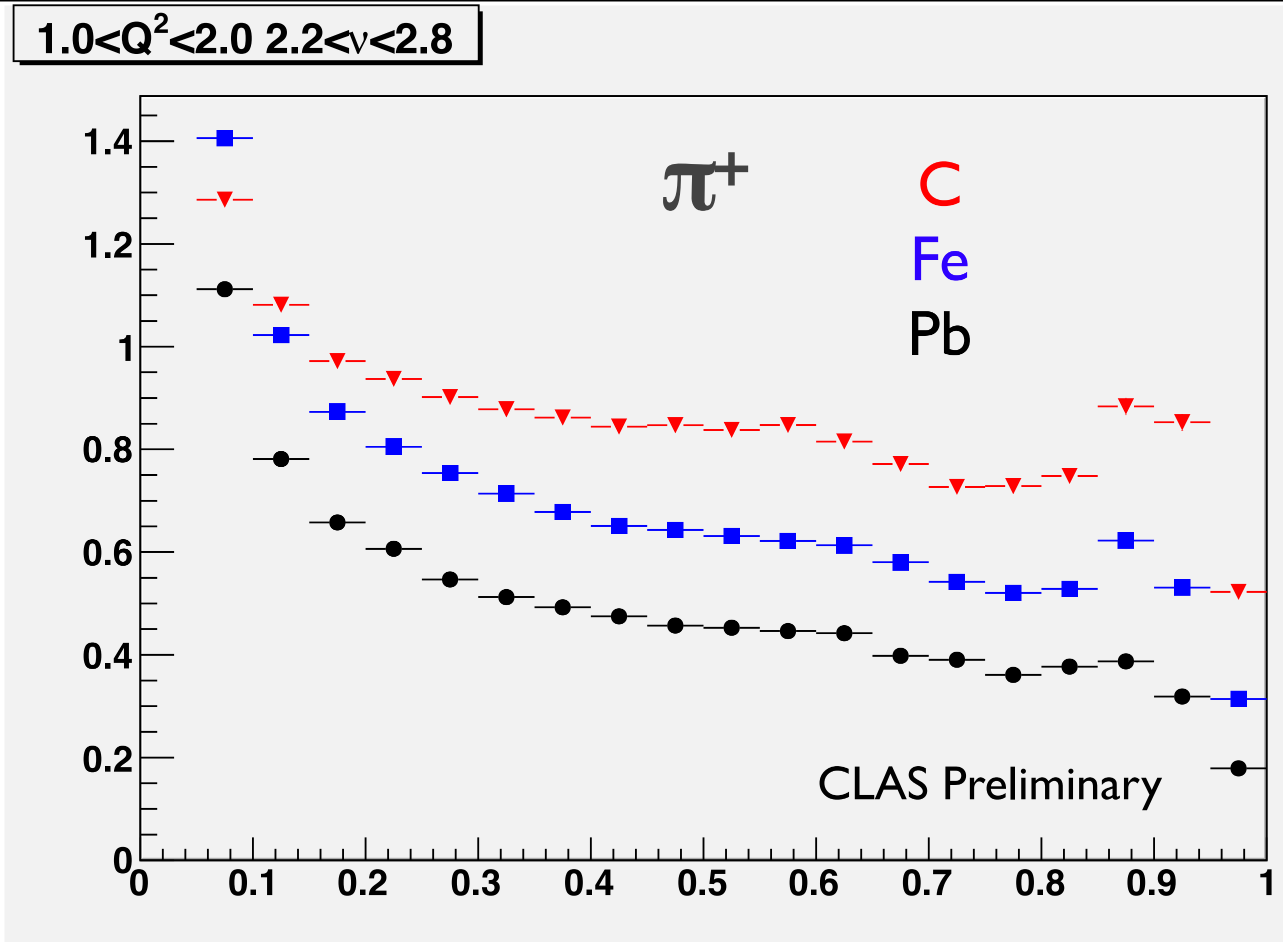
A. Beraudo et al.,
arXiv:1204.4342

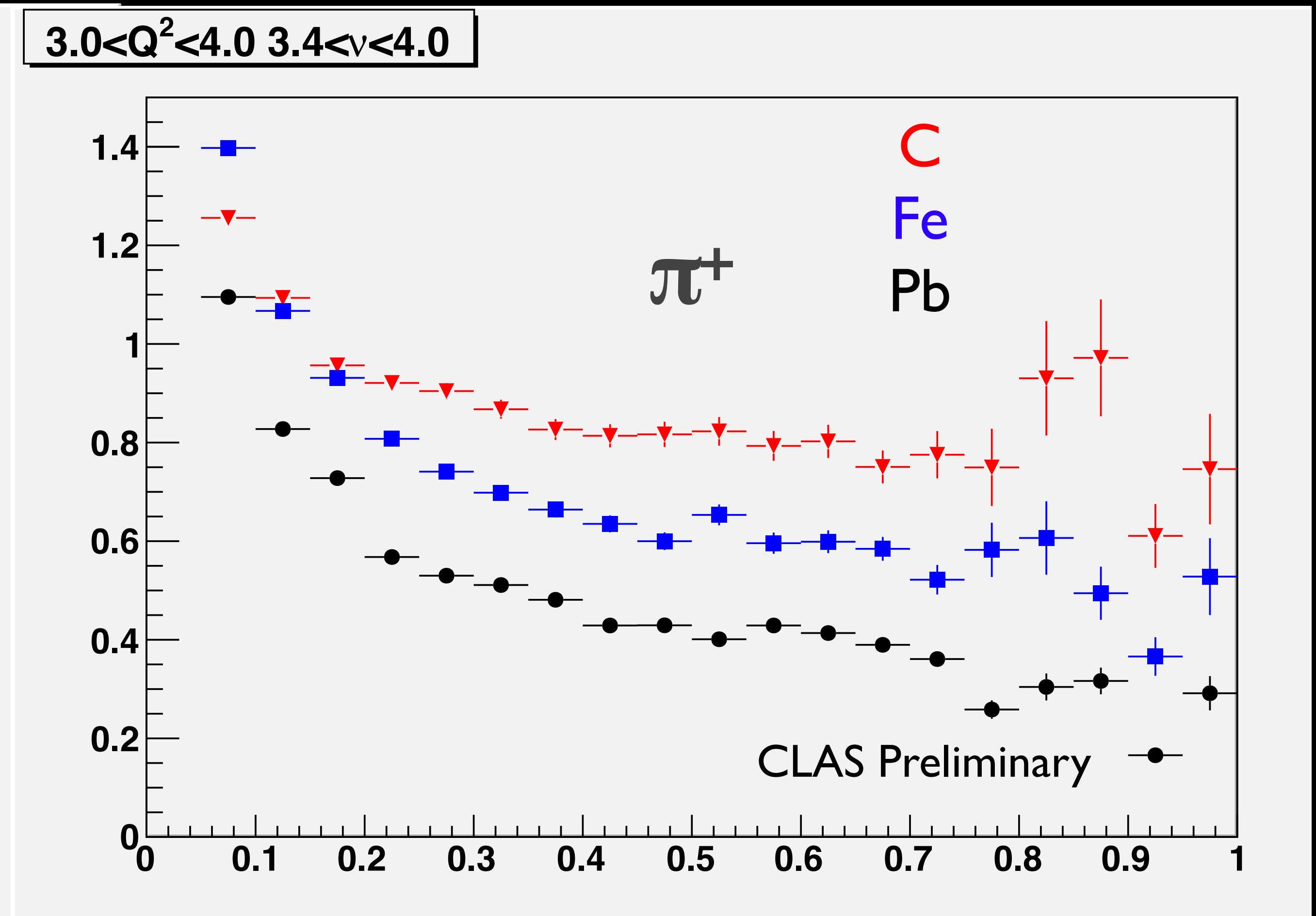


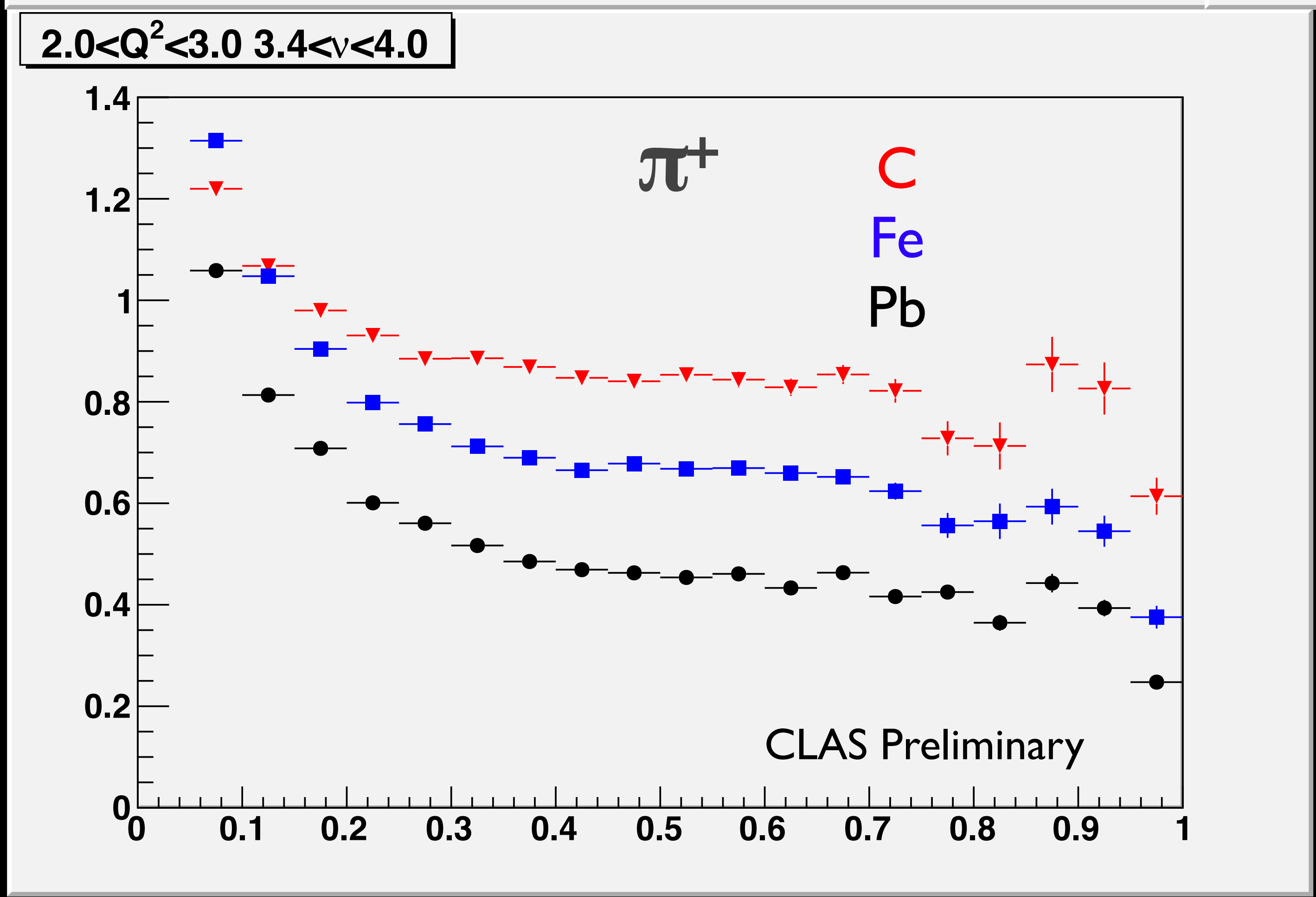
- Subleading string hadronizes separately
  -> enhanced soft multiplicity
- Leading string hadronizes vacuum-like
  but with reduced E_T

- Color connection between medium and probe
  also relevant for Quarkonium suppression

U.A. Wiedemann talk at QM2012







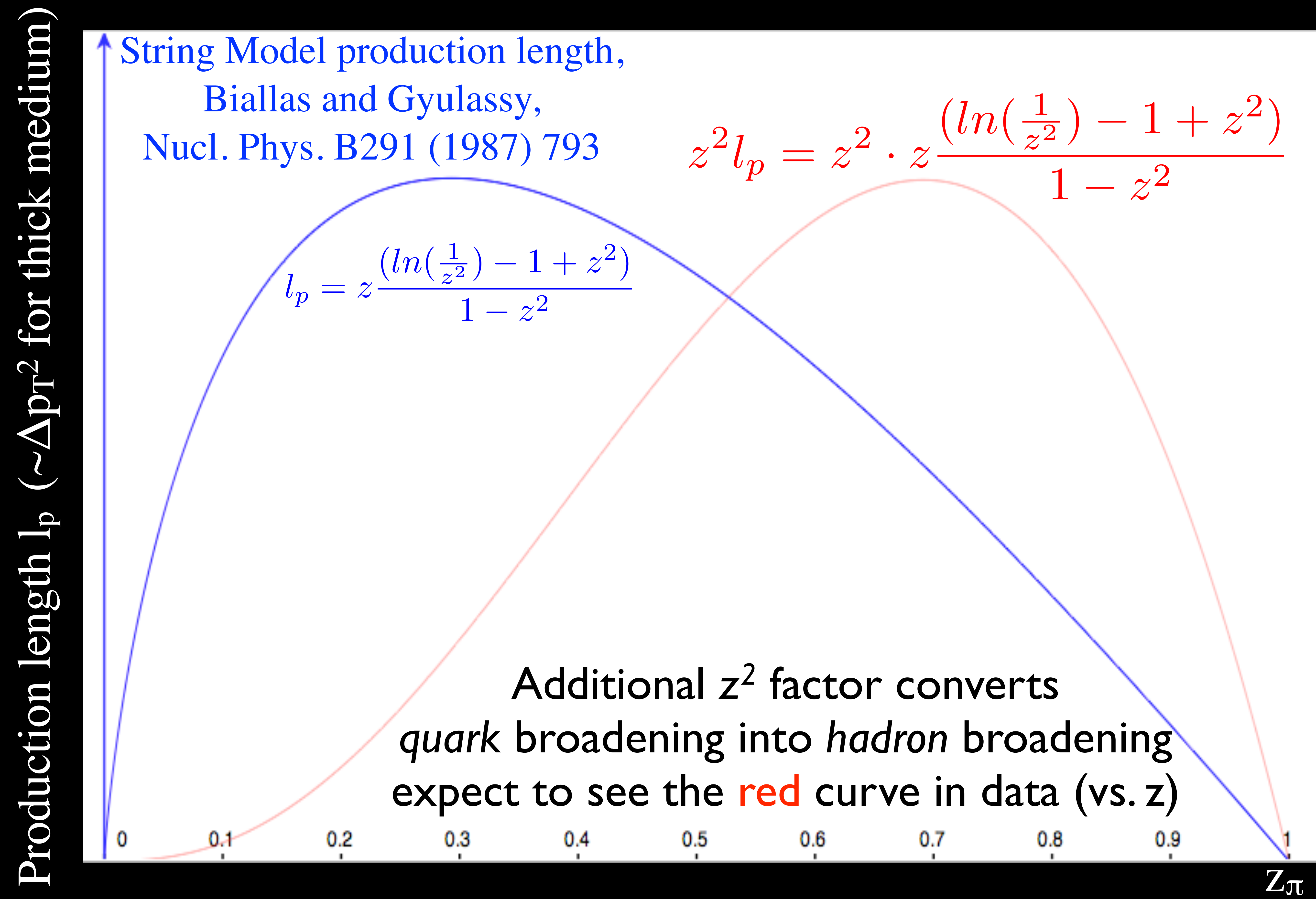
3-dimensional CLAS multiplicity ratios, fully corrected for radiative processes and acceptance, normalized to target thicknesses; C, Fe, Pb

(3 of many such plots)

also, K^0, π^0, π^-

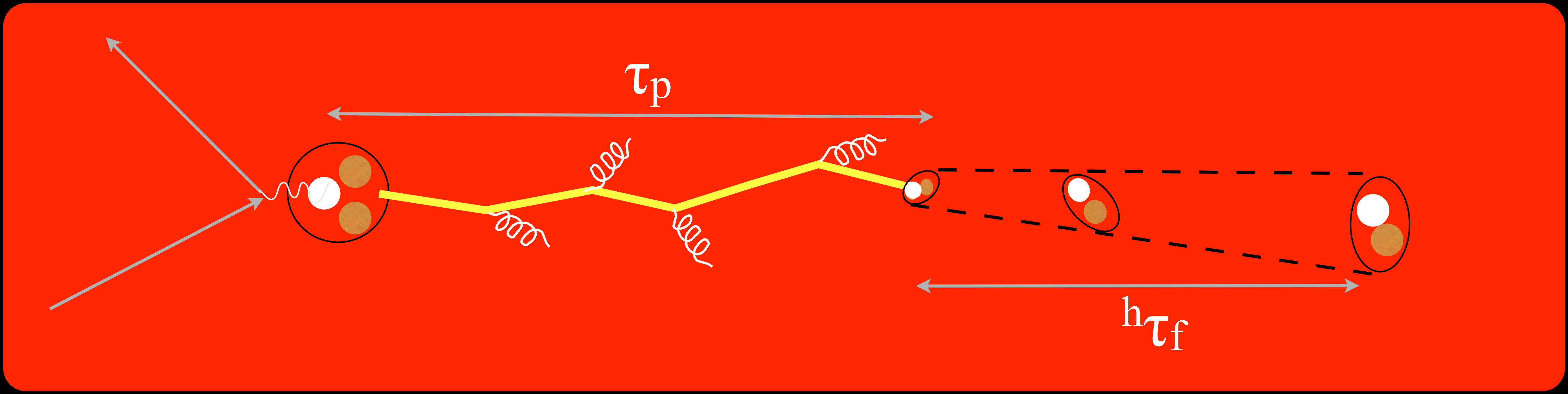
HERMES, JLAB6, JLAB12, p-A, EIC

- Two different explanations for HERMES data, no definitive differentiation yet
- parton energy loss, pre-hadron interaction with medium
- Models based on one view or the other, or a mixture, all describe the data at a similar level of quality
- EIC important to make a clear separation between hadronic and partonic effects



String Model production length,
Biallas and Gyulassy,
Nucl. Phys. B291 (1987) 793
$z^2 l_p = z^2 \cdot z \frac{(ln(\frac{1}{z^2}) - 1 + z^2)}{1 - z^2}$
$l_p = z \frac{(ln(\frac{1}{z^2}) - 1 + z^2)}{1 - z^2}$
Additional z^2 factor converts
quark broadening into *hadron* broadening
expect to see the red curve in data (vs. z)
Production length l_p ($\sim \Delta p_T^2$ for thick medium)
z_π
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Deep Inelastic Scattering - Vacuum



- <u>*production time* t$_p$</u> - propagating quark
- <u>*formation time* ^{h}t$_f$</u> - dipole grows to hadron
- <u>*partonic energy loss*</u> - *dE/dx via gluon radiation in vacuum*

Exploring nuclei with partonic probes

- $x>0.1$
  - *ensures single quark propagating with initial energy* ν
- p_T broadening tags propagation of colored object
  - *extraction of "production time"/"color neutralization time" at low* ν
- inference of partonic broadening from hadronic broadening
  - *requires factor of* z^2
- systematic studies needed to understand properties of the probe, currently ongoing
  - *HERMES, JLab6, JLab12 provide the foundation for EIC studies*